Inorganic bromine in the marine boundary layer: a critical review

R. Sander, W. C. Keene, A. A. P. Pszenny, R. Arimoto, G. P. Ayers, E. Baboukas, J. M. Cainey, P. J. Crutzen, R. A. Duce, G. Hönninger, et al.

Atmos. Chem. Phys. Discuss., 3, 2963–3050, 2003
www.atmos-chem-phys.org/acpd/3/2963/

Atmospheric Chemistry and Physics Discussions

Inorganic bromine in the marine boundary layer: a critical review

R. Sander[1], W .C. Keene[2], A. A. P. Pszenny[3], R. Arimoto[4], G. P. Ayers[5], E. Baboukas[1], J. M. Cainey[6], P. J. Crutzen[1], R. A. Duce[7], G. Hönninger[8], B. J. Huebert[9], W. Maenhaut[10], N. Mihalopoulos[11], V. C. Turekian[12], and R. Van Dingenen[13]

[1]Air Chemistry Department, Max-Planck Institute of Chemistry, P.O. Box 3060, 55020 Mainz, Germany
[2]Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903, USA
[3]Center for Global Change Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. Now at: Climate Change Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, and Mount Washington Observatory, P.O. Box 2310, North Conway, NH 03860, USA
[4]CEMRC/New Mexico State University, 1400 University Drive, Carlsbad, NM 88220, USA
[5]CSIRO Atmospheric Research, Private Bag No. 1, Aspendale 3195, Australia
[6]Cape Grim Baseline Air Pollution Station, 159 Nelson Street, Smithton, Tasmania 7330, Australia

[7]Depts. of Oceanography and Atmospheric Sciences, Texas A&M University, TAMU-3146, College Station, TX 77843-3146, USA
[8]Institut für Umweltphysik, Universität Heidelberg, INF 229, 69120 Heidelberg, Germany. Now at: Meteorological Service of Canada, 4905 Dufferin Street, Toronto, Ont. M3H 5T4, Canada
[9]Department of Oceanography, University of Hawaii, 1000 Pope Road, Honolulu, HI 96822, USA
[10]Ghent University, Department of Analytical Chemistry, Institute for Nuclear Sciences, Proeftuinstraat 86, B-9000 Gent, Belgium
[11]Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, P.O. Box 1470, 71409 Heraklion, Greece
[12]National Academy of Sciences, 2101 Constitution Ave. NW, Washington, DC 20418, USA
[13]European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, T.P 290, I-21020 Ispra (VA), Italy

Received: 2 April 2003 – Accepted: 12 May 2003 – Published: 2 June 2003

Correspondence to: R. Sander (sander@mpch-mainz.mpg.de)

Abstract

The cycling of inorganic bromine in the marine boundary layer (mbl) has received increased attention in recent years. Bromide, a constituent of sea water, is injected into the atmosphere in association with sea-salt aerosol by breaking waves on the ocean surface. Measurements reveal that supermicrometer sea-salt aerosol is depleted in bromine by about 50 % relative to conservative tracers, whereas marine submicrometer aerosol is often enriched in bromine. Model calculations, laboratory studies, and field observations strongly suggest that these depletions reflect the chemical transformation of particulate bromide to reactive inorganic gases that influence the processing of ozone and other important constituents of marine air. However, currently available techniques cannot reliably quantify many Br-containing compounds at ambient concentrations and, consequently, our understanding of inorganic Br cycling over the oceans and its global significance are uncertain. To provide a more coherent framework for future research, we have reviewed measurements in marine aerosol, the gas phase, and in rain. We also summarize sources and sinks, as well as model and laboratory studies of chemical transformations. The focus is on inorganic bromine over the open oceans, excluding the polar regions. The generation of sea-salt aerosol at the ocean surface is the major tropospheric source producing about 6.2 Tg/a of bromide. The transport of Br from continents (as mineral aerosol, and as products from biomass-burning and fossil-fuel combustion) can be of local importance. Transport of degradation products of long-lived Br-containing compounds from the stratosphere and other sources contribute lesser amounts. Available evidence suggests that, following aerosol acidification, sea-salt bromide reacts to form Br_2 and BrCl that volatilize to the gas phase and photolyze in daylight to produce atomic Br and Cl. Subsequent transformations can destroy tropospheric ozone, oxidize dimethylsulfide (DMS) and hydrocarbons in the gas phase and S(IV) in aerosol solutions, and thereby potentially influence climate. The diurnal cycle of gas-phase Br and the corresponding particulate Br deficits are correlated. Higher values of Br in the gas phase during daytime are consistent with

ACPD

3, 2963–3050, 2003

expectations based on photochemistry. Mechanisms that explain the widely reported accumulation of particulate Br in submicrometer aerosols are not yet understood. We expect that the importance of inorganic Br cycling will vary in the future as a function of both increasing acidification of the atmosphere (through anthropogenic emissions) and climate changes. The latter affects bromine cycling via meteorological factors including global wind fields (and the associated production of sea-salt aerosol), temperature, and relative humidity.

1. Introduction

The first atmospheric bromine measurements (in rain) were probably made by Marchand (1852). The next data were obtained more than 100 years later (Behne, 1953). Aerosol bromine was first measured by Duce et al. (1963) at Hawaii. Inorganic bromine compounds, especially Br, BrO, and HOBr, are reactive and have the ability to destroy ozone catalytically. It is known that they contribute to the destruction of the stratospheric ozone layer (e.g. WMO, 1998). In addition, bromine may also affect ozone in the troposphere. Zafiriou (1974) was the first to notice that halogen atoms in the marine boundary layer (mbl) would rapidly react with ozone. Summaries of these early results were presented by Duce and Hoffman (1976), Berg and Winchester (1978), Cicerone (1981), and Sturges and Harrison (1986b). Today, many new measurements are available which were made subsequent to these reviews. Several field experiments have shown the importance of tropospheric bromine chemistry in polar regions during spring (e.g. Barrie et al., 1988) and near salt lakes (e.g. Hebestreit et al., 1999). Apparently, reactions involving frozen sea water or solid salt crystals play a role there. However, the global role of marine bromine chemistry is still uncertain.

This review focuses on inorganic bromine chemistry over the open oceans, excluding the polar regions. We have compiled atmospheric measurements of inorganic bromine in marine aerosol, rain drops, and the gas phase. We also review model studies and laboratory measurements. Available data have been assembled and analyzed to gain

insight concerning the physical and chemical processes that control inorganic bromine in the mbl. Specific questions that are addressed include:

- How does the chemical aerosol composition vary with particle size?
- How does it change with altitude and latitude?
- What are the diurnal and seasonal variations?
- Is particulate bromine in marine air correlated with ambient acids and sea-salt concentrations?
- Are there bromine sources in addition to sea salt?

2. Measurement techniques, data quality and analysis

2.1. Aerosol measurements

Particulate bromine as well as sea-salt reference species (e.g. Na, Mg) and crustal reference species (e.g. Al) have been measured in marine air using several approaches. The most common techniques involve sampling aerosol over periods of hours to days either in bulk on a single filter (e.g. Kritz and Rancher, 1980) or as a function of size using either a 2-stage stacked filter unit (SFU) (e.g. Raemdonck et al., 1986) or inertial, multi-stage cascade impactors (CI) (e.g. Duce et al., 1965). Samples are then analyzed using various approaches including neutron activation analysis (NAA) for total Br, Na, Mg, and Al (e.g. Arimoto et al., 1987), atomic absorption spectroscopy (AAS, also abbreviated AA) for total Na and Mg (e.g. Galloway et al., 1982), ion chromatography (IC) for Br^-, Na^+, and Mg^{2+} (e.g. Ayers et al., 1999), X-ray fluorescence (XRF) for total Br and Na (e.g. Sturges et al., 1985), and particle-induced X-ray emission (PIXE, also called proton-induced X-ray emission) for total Br, Na, and Mg (e.g. Andreae, 1982). Recently, several aerosol mass spectrometers have been developed to analyze the

molecular (or molecular fragment) composition of single particles as a function of size (PALMS = particle analysis by laser mass spectrometry (Murphy et al., 1997); ATOFMS = aerosol time-of-flight mass spectrometry (Gard et al., 1998); AMS = aerosol mass spectrometry (Jayne et al., 2000)).

Bromide (Br^-) is the dominant form of inorganic bromine in sea water (Stumm and Brauner, 1975). It is therefore tempting to assume that all of the inorganic bromine in sea-salt aerosol samples is also bromide. However, one has to be aware that this is not necessarily the case. If the samples are analyzed by neutron activation (NAA), all chemical forms of bromine are detected. If ion chromatography (IC) is used, Br^- is detected exclusively. In this paper, we use the term 'bromine' and the symbol Br to denote the total of all inorganic bromine compounds. We only use 'bromide' if the ion Br^- is meant specifically.

In addition to potential differences resulting from species-specific versus non-specific measurement techniques, several other factors can influence the comparability of the resulting data. The geometry of inlets and associated sampling rates impart an effective upper limit for the size of aerosols sampled by different devices. In addition, physical effects such as non-isokinetic flow at sampler inlets (e.g. Rader and Marple, 1988) or wall losses within inlets (e.g. Huebert et al., 1990) may introduce significant bias, particularly in the collection of supermicrometer aerosol from aircraft. Consequently, vertical profiles of sea-salt composition are very poorly constrained. Cascade impactors may also experience significant internal losses of particles (e.g. Willeke, 1975). Finally, the current generation of aerosol mass spectrometers is not capable of analyzing larger marine aerosol which dominate the flux of atmospheric sea salt and related compounds. Reported data from these instruments are limited to the lower end of the sea-salt size distribution (less than about 3 μm diameter). The above limitations in our ability to reliably characterize the upper end of marine aerosol size distributions contribute to the wide range in estimated fluxes of sea salt (e.g. Andreae, 1995; Graedel and Keene, 1995) and associated compounds.

A possible explanation for outliers could be improper blank correction when

Nuclepore® filters are used. The blank values of Br can be quite high and they can vary substantially from lot (batch) number to lot number.

Another concern is the possibility of a change in composition during the collection process. Mixing chemically distinct particles on sampling media (e.g. highly acidic sulfate aerosol with sea-salt aerosol on bulk filters) can lead to volatilization of HCl via acid displacement reactions. Fortunately, this is not the case for bromine because the effective solubility of HBr is much larger than that of HCl. Recent paired measurements of particulate Br in size-segregated and bulk aerosol samples collected in coastal air at Hawaii confirm that Br in bulk aerosol samples is conservative (Pszenny et al., manuscript in preparation).

However, gases such as HOBr in air streams may chemically interact with previously sampled aerosols on collection media (as they do in the atmosphere) during the relatively long exposure times (hours) required for most conventional measurement techniques. Such processes could cause significant post-collection artifacts. To our knowledge, the potential magnitudes of such bias in the measurement of particulate Br have not been critically evaluated.

Sampling locations and times may not be representative, thereby potentially impacting comparability among reported data. For instance, enhanced turbulence in coastal zones (surf) produces locally high concentrations of sea salt relative to off-shore locations. Sharp altitudinal gradients in sea salt (e.g. Blanchard et al., 1984) lead to substantial variability in measured concentrations as a function of sampling height. Since sea-salt aerosol production strongly depends on wind speed (Gong et al., 1997, and references therein), temporal variability in wind fields leads to large changes in sea-salt aerosol concentrations (e.g. Erickson et al., 1999). Finally, the relative amounts of sea salt and of acids and bases (both natural and anthropogenic) in the multiphase system vary as functions of proximity to and strengths of their respective upwind sources. Chemical interactions of this mixture together with ambient relative humidity control aerosol pH (Keene and Savoie, 1998, 1999; Erickson et al., 1999; Keene et al., 2002) and related pH-dependent processes involving particulate Br (e.g. Keene et al., 1998;

Ayers et al., 1999).

2.2. The enrichment factor EF

Absolute concentrations of aerosol bromine in the mbl can vary over a large range. The flux of sea-salt Br is mainly a function of wind speed which drives the generation of sea-salt particles. Thus, it is often useful to interpret bromine data relative to conservative constituents of sea salt. The elemental composition of sea water is shown in Table 1. In the absence of significant mineral dust, Na and Mg are generally conservative tracers of sea salt in the mbl (e.g. Keene et al., 1986). They are major components of sea salt and stable ions that are not known to undergo chemical reactions in the atmosphere. However, at low concentrations typical of submicrometer marine aerosol, random analytical variability can lead to relative large uncertainties.

Other constituents of sea-salt aerosol including Ca, K, and Cl have also been used as tracers of the sea-salt component. However, these tracers are often not conservative. For example, crustal dust contains significant Ca and K; biomass burning emits particles enriched in K; and Cl is displaced from acidified sea-salt aerosols as HCl. In addition, for some techniques (e.g. AAS), the analytical resolutions for Ca and K are relatively lower than those for Na and Mg. In some of the older Br data sets, paired measurements of Na or Mg were not reported. In such cases, other sea-salt tracers were used (see column 4 in Table 2), which makes the estimates of bromine enrichments less certain. In particular, several early papers used Cl as the reference species. In very remote regions where chlorine deficits relative to sea salt are typically low, errors will be small. However, in polluted regions where chlorine deficits are large (e.g. Keene et al., 1990; Sander and Crutzen, 1996), significant bias is associated with this approach.

For the ease of data evaluation, we define a dimensionless enrichment factor EF(Br)

ACPD
3, 2963–3050, 2003

for bromine, using Na as a reference element, as follows:

$$EF(\mathrm{Br}) = \frac{([\mathrm{Br}]/[\mathrm{Na}])_{\mathrm{meas}}}{([\mathrm{Br}]/[\mathrm{Na}])_{\mathrm{seawater}}} \quad (1)$$

where square brackets denote concentrations and 'meas' stands for 'measured'. Analogous definitions can be made for other sea-water elements. In this paper we abbreviate $EF(\mathrm{Br})$ as EF. When the enrichment factor of another element (e.g. Cl) is mentioned, it will be denoted explicitly as $EF(\mathrm{Cl})$.

Some authors report relative bromine *depletions* rather than enrichment factors. The simple relationship between them is:

$$\text{depletion} = 1 - EF \quad (2)$$

We prefer EF here because it avoids the complication of 'negative depletion' in the case when the aerosol is enriched in bromine, i.e. when $EF > 1$.

Although substantially enriched in organic constituents (Turekian et al., 2003), available evidence suggests that fresh sea-salt aerosol has an inorganic composition indistinguishable from that of surface seawater, i.e., $EF = 1$ (Duce and Woodcock, 1971; Duce and Hoffman, 1976).

While the dimensionless quantities EF and 'depletion' describe the *relative* composition, we will use the terms 'excess' and 'deficit' to refer to *absolute* quantities (e.g. expressed as mass per volume of air). We define 'excess Br' as the concentration of aerosol bromine in addition to that originating from sea salt:

$$\text{excess Br} = [\mathrm{Br}]_{\mathrm{meas}} - \left[[\mathrm{Na}]_{\mathrm{meas}} \times \left(\frac{[\mathrm{Br}]}{[\mathrm{Na}]}\right)_{\mathrm{seawater}}\right] \quad (3)$$

The simple definition of the deficit is:

$$\text{Br deficit} = -\text{excess Br} \quad (4)$$

ACPD
3, 2963–3050, 2003

Absolute quantities are especially useful when analyzing size-segregated data as shown in Sect. 4.1. Values for different size bins can simply be added up. If the total value of 'excess Br' is negative, it yields a rough estimate of what to expect in the gas phase, assuming that bromine originates from sea water and is just cycled between the phases.

2.3. Measurements of inorganic gas-phase species

As discussed in more detail below, chemical characterization of marine aerosol often reveals substantial enrichments in submicrometer Br and large deficits in supermicrometer Br relative to sea salt. These observations indicate that Br actively cycles between phases. The most likely forms of gas-phase bromine involved in such transformations include Br_2, BrCl, IBr, Br, BrO, HOBr, $BrNO_2$, $BrNO_3$, HBr, and possibly other species (e.g. Behnke et al., 1994; Sander and Crutzen, 1996; Vogt et al., 1996, 1999; Sander et al., 1999). Several techniques have been developed to quantify gas-phase Br.

The most widely used approach employs an alkaline-impregnated filter positioned downstream of a filter that removes particulate Br from the air stream. Available evidence suggests that such filter-pack devices efficiently sample reactive inorganic Br while effectively discriminating against organic Br gases (Rahn et al., 1976; Li et al., 1994). As for gas-phase Cl (Berg and Winchester, 1978), activated charcoal sampling media (Moyers and Duce, 1972) probably efficiently collect both inorganic and organic forms of gas-phase Br. Several potential artifacts are associated with the use of filter-pack samplers. Reactions on the upstream bulk filter between constituents of chemically distinct aerosols or between particulate-phase species and gases in the sample air stream could lead to positive or negative bias in volatile Br sampled downstream. In addition, the specificity of such samplers for most Br compounds has not been critically characterized via testing with calibration gases.

Tandem mass spectrometry (Spicer et al., 1998) and long path differential optical absorption spectroscopy (LP-DOAS) (Hebestreit et al., 1999; Martinez et al., 1999) have been used to measure Br_2 and BrO, respectively, in marine air. Detection limits for the

current generation of these instruments are near the upper limits of model-calculated mixing ratios over the open ocean. Consequently, most deployments to date do not have adequate resolution to reliably discern signal from noise in the mbl at lower latitudes. However, the development of Multi-Axis DOAS (MAX-DOAS) (Hönninger, 2002; Hönninger and Platt, 2002; Leser et al., 2003) allows very sensitive measurements of BrO in the planetary boundary layer. Recently, BrO was identified in the mbl of the North Atlantic using this new approach (Leser et al., 2003).

Techniques have been developed to measure mixing ratios of Br-atom precursors (primarily Br_2 and HOBr) (Impey et al., 1997) and to infer Br-atom concentrations based on relative concentration changes in hydrocarbons (Jobson et al., 1994) under conditions of enhanced Br chemistry during sunrise in the Arctic. However, such approaches probably lack adequate sensitivity to reliably characterize these species in marine regions at lower latitudes.

2.4. The detection limit

Differences in methods used to address measured concentrations below the analytical detection limit (DL) are an important and often overlooked factor influencing the comparability of reported data sets. Since particulate bromine in marine air is typically present at low concentrations relative to the resolution of current analytical techniques or the blank level of the filter material, most data sets include a significant fraction of observations below the DL. Some laboratories report only detectable concentrations. Others convert measured concentrations below zero (which occasionally result from random analytical variability around low ambient concentrations) to zero. A third approach sets all values less than the DL to the DL. All of these approaches cause positive bias in resulting population statistics. Some laboratories employ an alternative approach of setting all measured concentrations less than the DL (both positive and negative) to zero, which results in negative bias in population statistics. To minimize bias of this nature, values below the DL are sometimes set to 0.5 times the DL. However, the lower limits on distributions established by this approach reflect laboratory-specific analytical

resolution rather than ambient concentrations. Finally, some laboratories report concentrations as measured, including both positive and negative values less than the DL. This approach retains analytical uncertainties in the lower end of concentration distributions, which results in apparently 'noisier' data. Assuming that the measurements are unbiased, however, this latter approach yields the most representative population statistics. Because the method for handling concentrations below the DL is often not specified in reports, it is impossible to explicitly evaluate the potential importance for the comparability of all data reviewed herein. Undoubtedly, however, some of the observed differences at the lower end of concentration distributions result from such effects.

3. Compilation of measurements

Since the early 1960s, particulate bromine has been measured in most regions of the mbl (see Fig. 1). Available data sets, many previously unpublished, are summarized in Table 2. The abbreviations shown in the first column are used throughout the text to refer to individual data sets. Readers are referred to the original publications for detailed information concerning previously reported results. Unpublished data sets are briefly described in this section.

Between 1988 and 1998, the composition of marine aerosol sampled in bulk was measured as part of the Atmosphere-Ocean Chemistry Experiment (AEROCE). Amongst other elements, the particles were analyzed for Br, Cl, and Na. North Atlantic data sets are available from three mbl tower sites at Barbados (BAB8897), Bermuda (BEM8897), and Mace Head, Ireland (MHD8994), and also from one high-elevation (2360 m above sea level) site at Izaña, Tenerife (TEN8997). AEROCE-related investigations also characterized the chemical composition of size-segregated aerosols in the mbl as part of intensive field experiments at Barbados (BAB94), Bermuda (BEM93, BEM96, BEM97, BEM98), Mace Head (MHD93), and Punta del Hidalgo, Tenerife (TEN94). An additional, size-segregated data set was generated at the joint Texas A&M University – University of Hawaii tower on the windward coast of Oahu, Hawaii, in

autumn 1999 (HAW99). All of these sampling campaigns employed Graseby-Andersen hi-vol cascade impactors deployed on towers and operated under similar conditions. For data sets BAB94, BEM93, BEM96, and MHD93, the impactors were configured with an upper '0' stage, Whatman 41 substrates, and backup filters as described by Keene and Savoie (1998). For BEM97 and HAW99, the impactors were also configured with an upper '0' stage but aerosols were sampled on frosted polycarbonate (Lexan) impaction substrates and quartz fiber (Pallflex 2500 QAT-UP) backup filters (Pszenny et al., 1989; Keene et al., 2002). For BEM98, the upper '0' stage was not used and the standard impactors were configured with precombusted glass fiber substrates and backup filters (Turekian et al., 2001, 2003). Data sets BAB94, BEM93, BEM98, and MHD93 correspond to 24-hour or longer sampling intervals whereas those for BEM96, BEM97, and HAW99 were discrete daytime or nighttime sampling intervals.

The experiments at Enewetak (ENE79) and New Zealand (NZ83) were both conducted as part of the SEAREX (Sea/Air Exchange) program. The overall strategy for SEAREX was to sample the four major wind regimes, that is, the tradewinds and westerlies in both the Northern and Southern hemispheres, over the Pacific Ocean.

Maenhaut et al. (unpublished) analyzed bromine in aerosols at several locations (ATL90, BIR9196, JAB9596, NOS91, NOS92, TEX91). Most of the samples were collected either from ships (ATL90, NOS91), a platform (NOS92) or from stations near the coast (BIR9196, TEX91). Only Jabiru (JAB9596) is at 60 km away from the coast. However, it is only slightly above sea level, and sea salt is quite important there. The NOS91 data was obtained from the two ships Alkor (NOS91a) and Belgica (NOS91b) which were located on a circle of 200 km in diameter in the North Sea with Belgica always downwind of Alkor (see Fig. 1). The NOS92 data was sampled at two heights: On deck (NOS92-DECK) and from the mast of the platform (NOS92-MAST). All samples, (except for ATL90) were collected with the Gent PM10 stacked filter unit (SFU) sampler equipped with a PM10 inlet which separates the aerosol into two size fractions: Coarse (2 to 10 μm aerodynamic diameter (AD)) and fine (< 2 μm AD). The collection surfaces were for the coarse fraction an 8 μm pore size Apiezon®-coated Nuclepore® poly-

carbonate filter and for the fine fraction a 0.4 μm pore size Nuclepore® polycarbonate filter. The ATL90 samples were also collected with a SFU, but without the PM10 inlet. Here, the coarse filter was a 5 μm pore size Nuclepore® polycarbonate filter.

Van Dingenen et al. (unpublished) collected aerosols during Polarstern cruise ANT XII/1 from Bremerhaven to Chile (ATL94). Sample collection was identical to the method by Maenhaut et al. as described above but without PM10 inlet. Several elements were measured, including Br, Cl, Ca, K, Zn, and Fe. Na was not measured, so the enrichment factors are calculated using Ca as the sea-salt reference element. A second Atlantic cruise on the Polarstern which followed almost the same course was conducted in 1996 (ATL96b). Size-segregated aerosols were collected in six different stages with a Sierra-Andersen hi-vol cascade impactor and analyzed by IC.

During 20 days of the HAW99 experiment (described above), Huebert et al. (unpublished) sampled particulate bromine in bulk on PTFE filters (HAW99b). Starting each day at midnight, aerosols were sequentially sampled over approximately 3-hour intervals (total n = 152). Samples were analyzed by IC.

In the Southern Indian Ocean long-term aerosol measurements were performed at two remote islands. At Amsterdam Island (AMS9298), size-segregated aerosols were collected on Whatman 41 substrates and backup filters by means of a six-stage Sierra-Andersen hi-vol cascade impactor. The sampling was sectored to eliminate possible local terrestrial sources. The sampling intervals were 24-hours or longer. At Crozet (CRO9698), aerosols were collected on PTFE filters with a sampling interval ranging between 24 and 48 hours. All samples were analyzed for major anions and cations by IC.

Available nonspecific measurements of gas-phase inorganic Br are summarized in Table 3 and measurements of BrO using the DOAS technique are summarized in Table 4. The abbreviations used to define the gas-phase data sets end with '-G'.

Bromine concentrations measured in rain are summarized in Table 5. Abbreviations for these data end with '-R'.

4. Results and discussion

Results of the aerosol bromine measurements mentioned above are presented in several figures. Most data sets used to produce the figures are also available in the electronic supplement (http://www.copernicus.org/EGU/acp/acpd/3/2963/supplement.zip) to this paper. Figure 2 shows that bromine is depleted from most bulk samples. Data sets for size-segregated measurements are shown individually in Fig. 3 and in a combined plot in Fig. 4. Absolute bromine concentrations and excess bromine relative to sea water are shown in Fig. 5 separately for submicrometer (radius $r < 1\mu$m) and supermicrometer aerosol. The size-resolved plots show that for almost all supermicrometer particles $EF < 1$. Submicrometer aerosol usually shows a Br/Na ratio higher than that of sea water. However, sea-salt concentrations in these size fractions are relatively low. In addition, the long atmospheric lifetimes for these submicrometer size fractions (5 to 10 days) increases the potential for crustal contributions from remote continental sources and thus, sea-salt reference species may not be conservative. Consequently, these enrichment factors are associated with substantially greater uncertainty and must be interpreted with caution. We return to this point in Sect. 4.1. Before we continue to analyze the data further, we first examine the few exceptions where bromine enrichment was found in bulk or supermicrometer sea-salt aerosol.

- Samples from the polluted North Sea (see Fig. 2) show a bulk $EF > 1$. This is due to a high bromine content in the submicrometer particles (see Sect. 4.1). Supermicrometer sea salt particles show the usual bromine depletion (see Fig. 5).
- The only other outlier of the bulk data sets is HAR83. It is possible that the aerosol was influenced by Arctic air which at that time of year (spring) shows increased bromine concentrations (e.g. Berg et al., 1983).
- Two data sets corresponding to samples collected at elevated locations inland from the coast indicate significant bromine enrichments. Duce et al. (1965) (HAW63-HILL) found that bromine was enriched relative to chlorine (their sea-salt

reference species) in inland (approximately 16 km, 2000 m elevation) relative to coastal samples. Sadasivan (1980) sampled aerosol near the west coast of India at an altitude of 1380 m and at a distance of about 65 km from the coast (INDXX). However, no such bromine enrichment was observed at Jabiru (JAB9596), which is 60 km away from the coast but only slightly above sea level. A potential explanation for these observations is fast release of bromine to the gas phase close to the coast, followed by particle loss and readsorption of gas-phase bromine onto the remaining particles. Such an effect has also been seen in a model study by Moldanová and Ljungström (2001).

– Murphy et al. (1997) report that their measurements (CGR95) are consistent 'with a slight enrichment of bromine'. However, this conclusion was based on less than 4 % of their PALMS spectra. When all spectra are used (including those with a signal to noise ratio < 1000) they find that bromine is below the DL in about 85 % of the particles.

– For the bromine enrichment of CGR79 we do not have a satisfactory explanation, especially since other campaigns performed at Cape Grim (CGR94, CGR9698) show bromine depletion.

4.1. Size dependence

Duce et al. (1967) were the first to observe that EF varies as a function of particle size. Since then, many other studies have confirmed this size dependence. Figure 3 shows several data sets obtained at marine sites throughout the world. The medians of these data sets are shown in a composite plot in Fig. 4. Most of the size distributions exhibit asymmetric U shapes with three distinct regions:

1. For very large particles, the composition approaches that of sea water ($EF \approx 1$).
2. Particles in the medium size range of a few μm diameter are depleted in bromine ($EF < 1$).

3. Very small particles often show high bromine enrichment ($EF \gg 1$).

These three regions are discussed in detail below.

1. Compared to smaller aerosols, the largest sea-salt particles are associated with both shorter atmospheric lifetimes against deposition and smaller surface/volume ratios. Consequently, rates of chemical processing (e.g. alkalinity titration) are slower (Erickson et al., 1999) and their average age is smaller. For these reasons, they deviate less from the sea-water composition than the smaller particles. However, since the largest sea-salt aerosols turn over at much faster rates (several hours versus a mass-weighted average of 1.5 to 2 days for all sea salt (Erickson et al., 1999), even relatively small bromine depletions in these size fractions reflect disproportionately greater percentages of the total Br flux to the gas phase. For example, applying the average dry-deposition velocities for each size fraction of the BEM98 data set (Turekian et al., 2003) to the corresponding average Br deficits clearly indicates that the largest aerosols often dominate this flux.

2. Medium-sized sea-salt particles between one and a few μm are usually depleted in bromine. A mechanism for the loss of bromine from marine aerosol to the gas phase has been presented by Vogt et al. (1996). They proposed a reaction cycle that releases Br_2 and BrCl from slightly acidified sea-salt particles, as discussed in detail in Sect. 6.

3. Submicrometer particles often show very high values of EF. Samples that do not show such an enrichment are mostly taken from remote regions (see AMS9298, PAC79, PAC82, and SAM76 in Fig. 3). A comparison of the Atlantic cruises ATL94 and ATL96b (Fig. 7b) shows high EF for many submicrometer particles during 1994 but $EF \approx 1$ in 1996. This may be related to biomass-burning plumes encountered during ATL94 (see Sect. 5.3) while low levels of CO measured in 1996 indicate clean air masses. In addition to analyzing the relative enrichment factor EF, it is thus also important to look at absolute concentrations of bromine and 'excess Br', as defined in Eq. (3) and plotted in Fig. 5. Since most data sets shown here are from SFU sampling, they are divided into only two size bins: submicrometer and supermicrometer aerosol. As expected, the submicrometer particles show positive excess bromine (red in Fig. 5)

and the supermicrometer particles negative values (blue). For many data sets, the absolute bromine concentration in submicrometer particles is too small to compensate the bromine deficit in supermicrometer particles and the total excess bromine (black in Fig. 5) is thus negative. However, all data sets from the polluted North Sea (TEX91, NOS91, NOS92, BIR9196) show median excess bromine greater than zero. This suggests contributions from a non-sea-salt (possibly anthropogenic) source to submicrometer bromine in this region. Potential sources are discussed in Sect. 5. Alternatively, these enhanced enrichments may be related to physical (e.g. submicrometer volume) or other chemical (e.g. solution acidity) differences in the aerosol populations associated with relatively greater concentrations of pollutants.

It is still an open question how the high bromine concentrations can be sustained in the submicrometer particles. At first glance, it seems logical that bromine that was previously released from sea-salt aerosol subsequently condensed onto these small particles which have a high surface/volume ratio. However, if there is a mechanism that transfers sea-salt bromine into the gas phase, why doesn't it work for submicrometer particles? The inorganic components of submicrometer marine aerosols are typically dominated by deliquesced, highly acidic sulfate compounds (Keene et al., 2002), which should facilitate Br activation. Indeed, Vogt et al. (1996) suggested that recycling through sulfate aerosol should enhance production of Br_2 and BrCl relative to that expected based only on reactions in sea-salt solutions. There are several potential explanations for this discrepancy:

First, it could be that submicrometer bromine exists in a form other than Br^-. This bromine would have to be in a chemically inert form that cannot be converted to volatile species like Br_2 and BrCl. It would then be possible for this form of bromine to accumulate in submicrometer aerosol. A way to investigate this is to compare measurements of total inorganic bromine made by NAA (or PIXE) with specific measurements of the bromide anion made with IC. Unfortunately, we are not aware of a campaign in which samples were analysed by both methods. However, we can compare the results obtained by different campaigns. Figure 4 shows similar enrichments in the fine fraction

for all methods (red, green, and black lines). Especially useful is a comparison between the data sets from Bermuda. For BEM93 and BEM96 bromine was analyzed by NAA. The analysis method changed to IC for BEM97 and BEM98. Although substantial interannual variability is evident, mean values for all submicrometer size fractions indicate $EF > 1$. This implies that the bromide ion Br^- is the main chemical form of bromine in these particles.

Alternatively, some submicrometer Br^- could be externally mixed with chemically distinct particles such as mineral aerosol, soot carbon, or organic carbon, which lack sufficient water and/or acidity to sustain Br recycling. However, available evidence based on model calculations and chemical analysis of single particles (e.g. Dentener et al., 1996; Anderson et al., 1996) suggests that most mineral aerosol and soot in the mbl are often associated with soluble reactive surface layers, which should sustain aqueous chemical pathways. In addition, high concentrations of dust and soot in the mbl are typically limited to regions downwind of arid continents and/or extensive fossil fuel and/or biomass burning, respectively. We observe no obvious evidence for similar spatial patterns in EF. In contrast to dust and soot, submicrometer organic carbon is produced primarily by gas-to-particle conversion. Most of it is internally mixed with inorganic constituents rather than externally mixed as isolated organic aerosols (Middlebrook et al., 1998). Consequently, it seems unlikely that external mixing with chemically distinct aerosol types could sustain substantial particulate bromine in marine air.

Finally, it is possible that some other as yet unidentified pathway(s) lead to the accumulation of Br^- in submicrometer aerosol. Resolution of this issue remains an open question.

It should be noted, though, that EF must be treated with caution here. Since sea salt occurs mainly in the supermicrometer range, there is only little Na and Mg in submicrometer aerosol. Calculating EF involves dividing by the concentration of the reference element and is therefore strongly dependent on the accuracy of the measurement of that species.

4.2. Altitudinal variation

It is important to note that the exact location of the sampling site plays a role. Aerosol and rain samples (HAW63 and HAW63-R) collected in Hawaii by Duce et al. (1965) showed a systematic increase of EF with distance from the shore and height above the sea. In general, the farther the sampling location is from the sea surface, the more the aerosol composition deviates from sea water. Duce and Woodcock (1971) compared particles taken at the top (24 m above sea level) and the bottom (4 m a.s.l.) of a sampling tower (see HAW67-BOTTOM and HAW67-TOP in Fig. 3). Only at the top they observed bromine depletion. At the bottom EF was close to unity. This can be explained by large but short-lived sea-salt particles close to the surface that have a composition very similar to sea water.

In another study, François and Maenhaut (1994) collected samples on the deck (NOS92-DECK, 27 m a.s.l.) and from a mast (NOS92-MAST, 45 m a.s.l.) of a platform in the North Sea. Data from both altitudes are compared in Fig. 6. Coarse mode Na decreases with altitude simply because of the vertical gradient in sea-salt aerosol mass. Coarse mode Br shows a similar decrease and thus, a significant difference of EF between these heights cannot be seen. There is almost no vertical gradient of sea-salt aerosol mass in the fine mode and a linear regression of Na_{mast} vs. Na_{deck} (Fig. 6e) yields a slope of 1.05 and a correlation coefficient of $r^2 = 0.993$ (after excluding one outlier). Bromine concentrations at both heights are also similar (Fig. 6f). However, due to a higher analytical standard deviation the correlation is not as good as for Na.

Even though these data show no dependence of EF on height up to 45 m a.s.l., it should be noted that model calculations by von Glasow et al. (2002a) predict that acid-catalyzed bromine activation is more efficient in higher layers of the mbl.

Sampling at even higher altitudes can change the results drastically. The station at Izaña, Tenerife is at 2360 m a.s.l. and often encounters free tropospheric air. The aerosol data set obtained here (TEN8997) shows little similarity with sea salt aerosol even though the site is on a small island in the Atlantic. Values of EF are distributed

ACPD
3, 2963–3050, 2003

between 0 and 40. The high variability is expected because sources of Na and Br other than sea salt are significant, e.g. crustal Na.

4.3. Latitudinal variation

High concentrations of bromine are observed every spring in the Arctic (e.g. Berg et al., 1983). A similar situation probably exists in the Antarctic (Wagner and Platt, 1998). Outside of the polar regions, there is no clear evidence for a dependence of EF on latitude. The bromine measurements plotted in Fig. 2 show no systematic variation with latitude. Data from two Atlantic cruises (ATL94 and ATL96b) are shown in Fig. 7. No clear correlation between latitude and EF can be seen. Evidently, if there is a dependence at all, it is masked by other factors. Anthropogenic pollution, aerosol acidity, biomass burning plumes, and mineral dust can all affect EF. However, there seems to be one indication for a latitudinal trend. As discussed below (see Sect. 4.5), the seasonal cycle of EF is very pronounced in the southern hemisphere, whereas it is more difficult to see in most data sets from the northern hemisphere.

4.4. Diurnal variation

Several studies have investigated the diurnal variation in gas-phase and particulate bromine. The results, however, are inconsistent. Moyers and Duce (1972) found that the gaseous bromine concentrations did not differ in samples collected during sunlight hours versus those collected at night (HAW69). Systematic diurnal variation in particulate bromine was also examined but the limited number of samples precluded a statistically meaningful evaluation. Size-segregated data from a more recent study at Bermuda during spring (BEM96) also reveal no discernable evidence for significant diurnal variation (Keene et al., unpublished). However, the resolution of that data set is limited by the relatively small number of samples coupled with dynamic meteorological conditions.

In contrast to the above, Rancher and Kritz (1980) measured large diurnal variabili-

ACPD
3, 2963–3050, 2003

ties in both gas-phase and particulate bromine during stable meteorological conditions over the tropical South Atlantic Ocean (ATL77). Gas-phase inorganic bromine was approximately two times greater during the day relative to night. Particulate bromine varied by similar magnitudes but was anticorrelated with highest concentrations at night. Recent measurements in coastal air at Hawaii during late summer also reveal persistent, large diurnal variabilities in both gas-phase (HAW99-G, see Fig. 8) and particulate (HAW99b, see Fig. 9) bromine. Maxima in daily EF values ranged from 0.22 to 1.2 and mimima from <DL to 0.33. Day-night patterns and absolute differences in concentrations were similar to those reported by Rancher and Kritz (1980). The consistency between results from these latter studies in different areas suggests that diurnal variation in gas-phase and particulate inorganic bromine is a characteristic feature of the mbl in at least some tropical and subtropical regions. Considering the effect of stratiform clouds, von Glasow et al. (2002b) were able to reproduce this diurnal cycle with the one-dimensional column model MISTRA.

4.5. Seasonal and long-term variation

The seasonal variation in aerosol bromine has been investigated by Ayers et al. (1999). Bromine in particles of $< 10\,\mu$m diameter was measured at Cape Grim from January 1996 until May 1997. They found the highest depletions in the (austral) summer. The reason for the seasonal cycle is probably changing aerosol acidity (see Sect. 4.6). More recent data from June 1997 until July 1998 (Ayers, unpublished) show that the seasonal variation continues as predicted. The complete data set (CGR9698) is shown in Fig. 10a. Very similar seasonalities were observed at Crozet (CRO9698, Fig. 10b), Amsterdam Island (AMS9298, Baboukas (2000)), and at Macquarie Island (MQI9597) in the Southern Ocean (as shown by Ayers et al. (1999) in their Fig. 12).

The long-term measurements made as part of AEROCE are also very useful for revealing seasonal trends. Figures 11a–c show the development of EF over time for Barbados (BAB8897), Bermuda (BEM8897), and Mace Head (MHD8994). Since there were several extreme outliers in the data sets we decided to use medians and not

means for our analysis. There is evidence for a seasonal variation at Barbados for the whole time and for Bermuda from 1988 to 1993. Again, EF reaches a maximum in the winter and a minimum in summer. For Bermuda since 1994 and for Mace Head, the seasonal variation (if any) is much less pronounced. A long-term study in Norway (BIR9196) does not show a consistent seasonal variation (Fig. 12), either. In summary, seasonal trends are most obvious in unpolluted regions of the southern hemisphere.

In addition to seasonal trends, it is also interesting to analyze the data for long-term variations. However, we cannot see any significant difference between the data from the beginning of AEROCE in 1988 and ten years later in 1998. Similarly, the measurements at Birkenes (BIR9196) do not show a long-term trend, either (see Fig. 12).

4.6. Correlation to acids

Laboratory studies show that bromine release is acid-catalyzed (see Sect. 7). Thus a correlation of bromine depletions with aerosol acidity is to be expected. Three data sets can be used to directly address this topic. Murphy et al. (1997) analyzed aerosols in clean marine air at Cape Grim (CGR95). They observed an anticorrelation of bromine with sulfate. Assuming that sulfate is a tracer for aerosol acidity, this indicates enhanced loss of bromine from the aerosol when the particles are acidified. The long-term studies by Ayers et al. (1999), which was also performed at Cape Grim (CGR9698), and by Baboukas (2000) at Crozet (CRO9698) confirm this result. The monthly mean bromine depletions show a strong correlation with methane sulfonic acid (MSA), which is shown in Fig. 10. Still, the acidification is not strong enough for significant loss of chloride via acid displacement, and EF(Cl) thus remains close to unity (also shown in Fig. 10).

Most acids in the mbl over the high-latitude southern ocean are of natural origin (Ayers et al., 1999) and consequently, loss of bromine to the gas phase reported in the above studies is a naturally occurring phenomenon that is not driven by anthropogenic pollutants. As noted by Ayers et al. (1999), however, during colder months at Cape Grim, when sea-salt concentrations are higher and ambient acids lower, bromine

enrichment factors are closer to one. Therefore, it is reasonable to speculate that the enhanced fluxes of acids from anthropogenic activities to the global mbl have increased both the spatial and temporal extent of bromine depletion and related chemical processes over the world's oceans.

4.7. Correlation to sea-salt concentration

Another observation made by Ayers et al. (1999) was that low EF values correlated well with low total concentrations of Na. A likely explanation involves acidity again. Since the pH of sea water is about 8, the production of sea-salt particles is a source of atmospheric alkalinity. Higher aerosol acidities are expected when the concentrations of sea salt particles and thus Na are low relative to acids.

The correlation to Na can also be seen at Crozet (CRO9698, Fig. 10b) and in the AEROCE data sets (BAB8897, BEM8897, MHD8994), as shown in Figs. 11j–l. If [Na] $> 10\,\mu g/m^3$, then in almost all cases $EF(Br) > 0.3$. It is interesting to compare $EF(Br)$ to $EF(Cl)$ in Figs. 11g–i. Since dechlorination is mainly driven by acid displacement, chlorine deficits indicate acidified particles. Bermuda is often heavily impacted by anthropogenic acids transported from North America and the associated acidification of sea-salt aerosol results in lower $EF(Cl)$ values compared to Barbados and Mace Head. The lowest $EF(Cl)$ are at low concentrations of Na. $EF(Cl)$ is never below 0.5 when the concentration of Na is above $5\,\mu g/m^3$. For Mace Head and Barbados, $EF(Cl)$ is close to 1. $EF(Br)$ is in a similar range for all three sites suggesting that the lack of strong aerosol acidification events at Barbados and Mace Head does not prevent debromination. This is consistent with models results (Keene et al., 1998) which show that strong acidification is necessary for chlorine release but bromine can already escape from only slightly acidic solutions around pH=5.5. It indicates that whenever atmospheric acidity is present at levels sufficient to titrate sea-salt alkalinity, substantial debromination occurs.

However, we note in this regard that mixing chemically distinct aerosols (e.g. supermicrometer sea salt and submicrometer sulfate on bulk filters) can cause artifact acid

displacement of HCl (e.g. Keene et al., 1990). Thus caution is warranted in interpreting chlorine deficits associated with bulk aerosol.

Wind speed directly influences these processes in several important respects. Sea-salt production increases as a power function of wind speed (Gong et al., 1997). Increased wind velocities lead to increased production fluxes of sea-salt aerosols and associated alkalinity, higher concentrations of atmospheric sea salt, increased mean sea-salt sizes and total aerosol surface areas (but decreased mean surface/volume ratio), decreased sea-salt lifetimes, decreased rates of gaseous uptake and loss from individual particles, and increased overall scavenging and deposition of acids (e.g. Woodcock, 1953; Erickson et al., 1999). It is evident from the above discussion that all of these effects will influence the rate and degree of aerosol acidification and associated debromination.

4.8. Gas-phase bromine species

Several measurements of unspecified gas-phase inorganic bromine have been made in the mbl since the 1960s (see Table 3). They typically show mixing ratios between 2 and 10 pmol/mol. This is slightly larger than the bromine missing from the aerosol as shown in Fig. 5.

In addition to the direct measurements, there is also indirect support for the existence of gas-phase bromine compounds. Enrichment factors in rain (Table 5) range from about 0.6 to 5. Most values are above one. In all cases the EF for rain is larger than those for aerosol particles collected during the same campaign. A likely explanation is that clouds and falling rain drops scavenge not only particulate bromine, but also soluble gas-phase bromine (e.g. HBr).

Ozone measurements have also been used to indirectly infer the presence of gas-phase bromine. Dickerson et al. (1999) analyzed diurnal variations of O_3 in the Indian Ocean and partly attributed the changes to bromine chemistry. Nagao et al. (1999) analyzed a long-term ozone record from Ogasawara Island in the subtropical Pacific. Their data showed pronounced ozone destruction at sunrise, especially in the win-

ter when ozone concentrations are high. Bromine chemistry was given as a potential explanation. Galbally et al. (2000) also suggested a bromine (and iodine) based mechanism to explain their observation of sunrise ozone destruction at Cape Grim. Nowak et al. (2001) speculate on the reaction of gas-phase BrO with dimethyl sulfide (DMS) to explain observed levels of dimethyl sulfoxide (DMSO). However, they conclude that this reaction cannot explain production of DMSO at night. Sciare et al. (2000) find that 2 to 3 pmol/mol of BrO can reproduce the observed daytime cycle of their DMS measurements.

Encouraged by these indications that reactive bromine exists in the mbl, there were several attempts to detect individual bromine species, especially BrO (see Table 4). Hebestreit et al. (1999) and Matveev et al. (2001) were able to detect very high mixing ratios of up to 176 pmol/mol BrO over the Dead Sea, Israel (ISR97-G) with LP-DOAS. Compared to the open ocean, however, the Dead Sea has a much higher bromide content and is also acidic with a pH<7 (Nishri and Stiller, 1997), which favors heterogeneous reactions releasing bromine (see also Sects. 6 and 7). Recently, Stutz et al. (2002) reported BrO mixing ratios up to 6 pmol/mol at the Great Salt Lake, USA (GSL00-G) even though it has bromide content lower than sea water. However, major differences between these salt lakes, which are usually surrounded by salt pans, and the open ocean are the large salt surface areas available for heterogeneous reactions on salt pans and the different ionic composition including pH of most salt lakes compared to standard ocean water. Therefore, these results are not representative for the mbl over the open ocean.

GOME (Global Ozone Monitoring Experiment) satellite observations of column-integrated BrO have been reported by several authors (Richter et al., 1998; Chance, 1998; Hegels et al., 1998; Wagner and Platt, 1998; Wagner et al., 2001). In both polar regions, enhanced BrO vertical column densities indicate boundary layer BrO regularly during the spring months. Except for the polar regions during springtime, however, the total BrO column is governed by BrO in the stratosphere. The relative contributions from the troposphere or even the mbl cannot be reliably separated from the total BrO

column.

However, comparison with total column measurements from the ground (e.g. Friess et al., 1999) or with measurements of the stratospheric BrO column from balloon-borne instruments (e.g. Pundt et al., 2000; Harder et al., 2000) allow derivation of the tropospheric BrO fraction. If uniformly distributed over the complete altitude range of the troposphere the inferred tropospheric BrO column can be converted to a mixing ratio of 1 to 2 pmol/mol BrO (SAOZ9798-G). Several attempts have been made to measure BrO in the mbl outside the polar regions, both at a clean remote site (HAW99b-G) and also at sites that are more polluted to varying degrees (MHD96-G, MHD97a-G, MHD97b-G, MHD98-G, TEN97-G, WEY96a-G, WEY96b-G, CRT00-G). The results from these LP-DOAS measurements indicate ambient concentrations around or below the DL of the respective instruments (about 1 to 3 pmol/mol) (Alicke, 1997; Allan, 1998; Hönninger, 1999; Hönninger, 2002).

Recently Leser et al. (2003) performed shipborne MAX-DOAS measurements during an Atlantic transect from 54°N to 34°S (ATL00-G). Between 37°and 30° N BrO was observed in the mbl with an average of 0.7±0.2 pmol/mol and maximum values reaching up to 2.4±2.1 pmol/mol. For the rest of the transect BrO ranged below the DL of 1 to 3.6 pmol/mol for individual measurements. In contrast to the LP-DOAS measurements mentioned above, which are only sensitive to the respective absorption path, MAX-DOAS provides some extent of vertical resolution with the maximum sensitivity over the lowest kilometer of the atmosphere.

In summary, except for a few data points, individual gas-phase inorganic Br compounds have not been reliably characterized in the mbl at lower latitudes. Total gas-phase inorganic Br has been measured at several locations and typically appears to be around a few pmol/mol.

5. Primary sources of inorganic bromine

Although most inorganic bromine in the marine troposphere is produced from the ocean surface in association with sea-salt aerosol, other sources must also be considered. This is especially relevant for the high enrichment factors observed in submicrometer particles. The Br/Na mass ratios of different materials are listed in Table 6.

5.1. Sea-salt production

The emission flux of particulate Br from the surface ocean to the atmosphere can be estimated from reported production fluxes of sea-salt aerosol and the measured composition of surface sea water. Based on the production flux of sea-salt chloride of 1785 Tg/a (Erickson et al., 1999) and the Br/Cl mass ratio of 0.00348 kg/kg (Table 1), we estimate a direct bromine production flux of 6.2 Tg/a from the surface ocean. This pathway is the principal global source for atmospheric Br.

5.2. Mineral aerosol

Strong winds during dry seasons sporadically inject large amounts of soil dust from semi-arid regions (primarily from northern Africa and central Asia) into the middle troposphere where it can be transported long distances over oceans by prevailing winds before removal via wet and dry deposition (Swap et al., 1992; Prospero et al., 1996). A well-known example is Saharan dust which can often be seen in marine aerosol samples. The element Al can be used as a conservative tracer for dust. In principle, it is possible to obtain the dust-derived contribution $[Br]_{dust}$ to the total bromine content:

$$[Br]_{dust} = [Al]_{meas} \times \left(\frac{[Br]}{[Al]}\right)_{dust} \quad (5)$$

where $[Al]_{meas}$ = measured Al concentration and $([Br]/[Al])_{dust}$ = elemental ratio typical for mineral aerosol. However, it is difficult to derive a value for the ratio Br/Al in dust because the composition of mineral aerosol is distinct from that of Earth's crust (Schütz

and Rahn, 1982) and also varies spatially. The bromine content of the continental crust is very low with $m(\mathrm{Br})/m(\mathrm{Al}) = 2.07\times10^{-5}$ kg/kg (Wedepohl, 1995). This value does not apply to airborne particles. Bromine concentrations in atmospheric dust near source regions are substantially greater than those in crustal rock. Since most dust originates from deflation of seasonally wetted soils (Prospero et al., 1996), this relative enrichment can be attributed in part to the dissolution, upward migration, and subsequent evaporative concentration of soluble salts near the soil surface over wet/dry cycles. Adepetu et al. (1988) analyzed dust in Nigeria that originated in the Sahara. Their 6 samples collected between 1981 and 1984 showed bromine enrichments from 10 to 300 relative to crustal rock and a mean value of $m(\mathrm{Br})/m(\mathrm{Al}) = 3.19\times10^{-3}$ kg/kg. They state that this enrichment could be due to bromine-containing pesticide residues and automobile exhaust in the local environment. Consequently, the data by Adepetu et al. (1988) probably represent upper limits for the bromine content of Saharan dust.

Approximately 73 Tg/a of mineral Al is deposited from the atmosphere to the world's oceans (Duce et al., 1991). Adopting the Br/Al mass ratio from Adepetu et al. (1988) as an upper limit and assuming similar atmospheric lifetimes for crustal Br and Al, we estimate that an upper limit of about 0.23 Tg/a of crustal Br is deposited to the world's oceans. Although this flux of crustal bromine is small (about 4 %) compared to the global flux of sea-salt bromine, most crustal bromine is deposited over the equatorial Atlantic and North Pacific Oceans, which lie downwind of the major dust source regions in North Africa and central Asia, respectively. Thus, the relative contributions of crustal to total bromine in these regions are considerably greater than the global average.

The chemical evolution of mineral aerosol is poorly understood (e.g. Dentener et al., 1996) and that of crustal bromine virtually unexplored. Assuming that water and acids accumulate on aging atmospheric dust (probably as aqueous surface films) (e.g. Dentener et al., 1996; Li-Jones et al., 1998), bromine activation reactions analogous to those in sea salt aerosol should proceed. Such reactions could have important implications for the chemical evolution of dust plumes.

5.3. Biomass burning

Biomass contains significant Br which is emitted to the atmosphere during combustion (e.g. Andreae et al., 1996; McKenzie et al., 1996). Based on the few available compound specific measurements, CH_3Br comprises relatively minor fractions (5 %) of the emitted Br (e.g. Andreae et al., 1996). As for Cl (e.g. Keene et al., 1999), it appears that most Br is emitted from burns in the form of volatile inorganic and particulate compounds. Particulate Br is enriched in biomass burning plumes, particularly from savanna fires (e.g. Echalar et al., 1995; Maenhaut et al., 1996b; Andreae et al., 1998; Kleeman et al., 1999). The relative importance of primary emissions versus secondary production cannot be reliably differentiated from such measurements. This raises the possibility that transformations involving Br radicals, analogous to those in marine air, may influence the chemical evolution of biomass-burning plumes. The advection of burning emissions over the ocean contributes combustion-derived Br to the multiphase mbl system. Particulate Br/Na and Br/Ca ratios in aged biomass burning plumes are greater than those in sea water (see Table 6) which complicates the interpretation of Br enrichment factors in marine air. Data from the experiments ATL94 and BEM98 provide context for assessing relative contributions of combustion-derived Br in marine regions significantly impacted by biomass-burning products.

During the ATL94 cruise between 10°S and 30°S in the Atlantic, EF relative to sea-salt Ca for fine-fraction aerosols ranged from 3 to 10 while the coarse fractions were depleted (Fig. 7). Ratios of particulate Zn/Ca and K/Ca (e.g. Maenhaut et al., 1996b) indicate the presence of significant biomass-burning emissions in this region suggesting that burning-derived Br may have contributed to the apparent fine-fraction enrichments relative to sea salt. However, the Br/Zn ratio characteristic of burning over southern Africa (Maenhaut et al., 1996b) suggests that 30 % to 80 % of the observed fine-fraction Br originated from sources other than biomass burning.

During BEM98, the western North Atlantic mbl was significantly impacted by emissions from extensive wildfires in Latin America and Florida that were associated with a

particularly strong El Niño (Turekian, 2000). The corresponding biomass burning emissions of Br probably explain why EF in the finer aerosol size fractions was higher than during other years at Bermuda (BEM93, BEM96, BEM97), as shown in Fig. 4.

5.4. Fossil-fuel combustion

Duce et al. (1965) suggested that some bromine may result from automobile exhaust. This is especially true for a polluted atmosphere (Moyers et al., 1972). However, it can also apply to the marine environment. Martens (1973) concluded that 'leaded aerosols appear to be a major source of bromine in small particles' for marine aerosols collected in Puerto Rico. Leaded petrol contains lead in the form of tetraethyl lead ($Pb(C_2H_5)_4$) which is a good tracer for automobile pollution. It also contains the additives 1,2-dibromoethane ($BrCH_2CH_2Br$) and 1,2-dichloroethane ($ClCH_2CH_2Cl$) (Hamilton, 1996). During the combustion process the lead and halogen compounds react and predominantly produce PbBrCl which is emitted into the atmosphere (Habibi, 1973). Thus a ratio $n(Br)/n(Pb) = 1\,mol/mol$ is expected for freshly emitted particles. This is equivalent to a mass ratio of $m(Br)/m(Pb) = 0.386\,kg/kg$ (Lininger et al., 1966; Harrison and Sturges, 1983). A study in urban Honolulu, Hawaii, by Jernigan et al. (1971) showed a strong correlation between Pb and Br in the particles. The portion of bromine resulting from sea salt was small even though the city is in the middle of the Pacific Ocean. A similar result was obtained by Sturges and Harrison (1986b): Aerosol collected at a coastal site in northwest England (MOR8283) also showed a strong correlation between Pb and Br. The ratio Br/Pb was close to that expected for petrol. To obtain the petrol-derived contribution to the bromine contents $[Br]_{petrol}$, a formula similar to Eq. (5) can be applied:

$$[Br]_{petrol} = [Pb]_{meas} \times \left(\frac{[Br]}{[Pb]}\right)_{petrol} \quad (6)$$

where $[Pb]_{meas}$ = measured Pb concentration and $([Br]/[Pb])_{petrol}$ is the elemental ratio typical for petrol. A very different result was obtained by Sturges (1990) at a site in

Scotland (HAR83). In this case contamination from petrol could not explain the high bromine content.

The decline in the world-wide use of leaded petrol (Thomas et al., 1997) is reflected in the atmosphere. For example, at Bermuda, aerosol lead concentrations have decreased by an order of magnitude from the 1970s to the mid-1990s (Huang et al., 1996). Since unleaded petrol does not contain the additive 1,2-dibromoethane, aerosol bromine from petrol has also decreased (Thomas et al., 1997). In India, leaded petrol has only recently been phased out. During the INDOEX measurements in the Indian Ocean (IND99), a steep gradient with increasing aerosol bromide concentrations towards the Indian coast was observed (Gabriel et al., 2002).

5.5. Other sources

Degradation of short-lived organobromine compounds like CH_3Br (e.g. Khalil et al., 1993; Yokouchi et al., 2000) and $CHBr_3$ (Quack and Wallace, 2003) via photolysis and reaction with OH also represents a source of inorganic bromine in the mbl. WMO (1998) lists global fluxes of 0.043 to 0.244 Tg/a of CH_3Br and 0.1965 Tg/a of $CHBr_3$. However, these numbers are upper limits for the contribution to inorganic reactive bromine because only a part of these molecules reacts in the mbl.

Degradation of longer-lived organobromine compounds in the stratosphere and subsequent downward transport is also a potential source. Accurate data are not available but nevertheless it is possible to get a rough estimate. Schauffler et al. (1998) measured a total organic bromine content near the tropopause of about 17.4 pmol/mol, i.e. a mass mixing ratio of 4.8×10^{-11} kg/kg. Multiplying this with an estimated downward mass exchange through the troposphere of 7.2×10^{16} kg/month (Grewe and Dameris, 1996) yields a source strength on the order of 0.04 Tg/a.

Other sources of bromine that have been proposed in the literature are coal burning (Duce et al., 1983) and volcanic emissions (Harrison and Sturges, 1983, and references therein). Swietlicki (1989) applied a principal component analysis to bromine data from 600 submicrometer aerosol samples collected at 3 Swedish sites in the Baltic

Sea (SWE8586). He concluded that 'bromine is found at elevated relative amounts following transport, implying a gas-to-particle conversion for this element during transportation'.

6. Modeling the mechanism of bromine chemistry in the MBL

From the previous sections it is clear that a substantial fraction of the bromine in sea-salt particles is transferred into the gas phase. The question is which chemical mechanism causes this.

One may think that acid displacement plays a role. Acid displacement is an important mechanism by which sea-salt particles lose chloride in polluted air, e.g. :

$$H_2SO_4 + Cl^- \rightarrow HCl_{(aq)} + HSO_4^- \quad (7)$$

$$HCl_{(aq)} \rightarrow HCl_{(g)} \quad (8)$$

An analogous reaction for bromine would be:

$$H_2SO_4 + Br^- \rightarrow HBr_{(aq)} + HSO_4^- \quad (9)$$

$$HBr_{(aq)} \stackrel{?}{\rightarrow} HBr_{(g)} \quad (10)$$

However, this pathway can be ruled out because HBr is about 600 times more soluble than HCl (Sander, 1999). Therefore most of the chloride would have escaped from acidified particles before evaporation of HBr starts. This is in contrast with measurements which show that chlorine depletions are almost always smaller than bromine depletions (see Figs. 10 and 11j–l). Thus a different mechanism must be responsible for debromination.

Under polluted conditions, the nitrogen oxides NO_2 and N_2O_5 can react with Br^- on the surface of sea-salt particles (Finlayson-Pitts and Johnson, 1988; Finlayson-Pitts et al., 1990; Behnke et al., 1994). This forms the gas-phase species BrNO and $BrNO_2$. However, in clean marine air, the concentrations of nitrogen oxides are low and

thus these reactions cannot explain the large bromine deficits measured in unpolluted regions of the mbl.

The first mechanism for low-NO_x conditions was proposed by Fan and Jacob (1992), though for a different environment: The reaction of HOBr with Br^- in Arctic sulfate aerosol particles:

$$HOBr + Br^- + H^+ \rightarrow Br_2 + H_2O \quad (11)$$

Mozurkewich (1995) noticed that this reaction would also be possible in acidified Arctic sea-salt particles. Using the box model MOCCA, Sander and Crutzen (1996) applied the mechanism to polluted marine air at mid-latitudes. Vogt et al. (1996) found a synergism between bromine and chlorine chemistry which makes the release of bromine possible even under clean air conditions. They proposed the reaction of HOBr with Cl^- as the key reaction of an autocatalytic cycle that converts relatively inert sea-salt bromide into reactive inorganic gas-phase bromine species. The complete cycle is:

$$HOBr + Cl^- + H^+ \rightarrow BrCl + H_2O \quad (12)$$

$$BrCl + Br^- \rightarrow Br_2 + Cl^- \quad (13)$$

$$Br_{2(aq)} \rightarrow Br_{2(g)} \quad (14)$$

$$Br_2 \xrightarrow{h\nu} Br + Br \quad (15)$$

$$Br + O_3 \rightarrow BrO + O_2 \quad (16)$$

$$BrO + HO_2 \rightarrow HOBr + O_2 \quad (17)$$

$$HOBr_{(g)} \rightarrow HOBr_{(aq)} \quad (18)$$

$$\overline{Br^- + H^+ + O_3 + HO_2 \xrightarrow{h\nu} Br + 2O_2 + H_2O}$$

This cycle is shown with red lines in Fig. 13. There are several alternative pathways that may contribute as well. For example, the direct reaction of HOBr with Br^- in Eq. (11) is equivalent to the sequence of reactions (12) and (13). If there is not enough bromide in the aerosol for reaction (13) to proceed, BrCl can volatilize. The photolysis of BrCl is

a source of reactive chlorine in the gas phase (see blue lines in Fig. 13). The additional effect of $BrNO_3$ chemistry was analyzed by Sander et al. (1999). $BrNO_3$ can hydrolyze or react with chloride or bromide:

$$BrNO_{3(g)} + H_2O \rightarrow HNO_3 + HOBr \quad (19)$$

$$BrNO_{3(g)} + Cl^- \rightarrow NO_3 + BrCl \quad (20)$$

$$BrNO_{3(g)} + Br^- \rightarrow NO_3 + Br_2 \quad (21)$$

This is represented by the green lines in Fig. 13. Note that reactions (20) and (21) can produce BrCl and Br_2 without the need of aerosol acidity.

In addition to their effect on aerosol bromide, these reaction cycles also influence ozone (thick lines in Fig. 13):

$$Br + O_3 \rightarrow BrO + O_2 \quad (16)$$

$$BrO + HO_2 \rightarrow HOBr + O_2 \quad (17)$$

$$HOBr \xrightarrow{h\nu} Br + OH \quad (22)$$

$$\overline{O_3 + HO_2 \xrightarrow{h\nu} 2O_2 + OH}$$

It should be noted here that the self-reaction of BrO, which is important in the Arctic tropospheric ozone depletion events during spring (e.g. Tuckermann et al., 1997), only plays a minor role in the mbl at mid-latitudes due to the lower concentration of BrO.

Several initialization reactions can start the autocatalytic bromine activation:

- $Br^- + O_3$ (Oum et al., 1998; Rudich et al., 1998; Hirokawa et al., 1998; Anastasio and Mozurkewich, 2002)
- $Br^- + OH$ (Mamou et al., 1977)
- $Br^- + NO_3$ (Sander and Crutzen, 1996; Rudich et al., 1998)
- $Br^- + N_2O_5$ (Finlayson-Pitts et al., 1990; Behnke et al., 1994)

- $Br^- + HSO_5^-$ (Mozurkewich, 1995)
- photolysis of organic bromine species (Moortgat et al., 1993)
- photolysis of organic iodine species and subsequent interaction with the bromine chemistry (Vogt et al., 1999)

Once a small amount of a reactive bromine species has been produced via one of these reactions, a steady state of modeled bromine release is reached quickly.

Bromine species can also affect sulfur chemistry. The rate of scavenging of SO_2 into aerosols is mainly determined by the rate at which it is oxidized in the aqueous phase. HOBr serves as another oxidant in addition to O_3 and H_2O_2:

$$HOBr + SO_3^{2-} \rightarrow HBr + SO_4^{2-} \quad (23a)$$

$$HOBr + HSO_3^- \rightarrow HBr + HSO_4^- \quad (23b)$$

Only the rate constant for reaction (23a) has been measured (Troy and Margerum, 1991). Assuming that reaction (23b) proceeds at the same rate, Vogt et al. (1996) found that it can contribute about 20 % to S(IV) oxidation. It will thus increase scavenging of SO_2 into the particles considerably.

Another link between bromine and sulfur chemistry exists in the gas phase, as pointed out by Toumi (1994):

$$DMS + BrO \rightarrow DMSO + Br \quad (24)$$

This reaction will reduce the overall yield of SO_2 resulting from DMS oxidation by the OH radical. Boucher et al. (2003) conclude that even BrO below 1 pmol/mol would be significant for DMS. Note that both reactions (23) and (24) reduce gas-phase SO_2. This leads to less H_2SO_4 in the gas phase with possible consequences for cloud microphysics and climate (Andreae and Crutzen, 1997).

Although models are able to explain the loss of bromine from sea-salt aerosol qualitatively, model-calculated EF are typically lower than those obtained from measurements. In Sect. 8, we list several ideas to improve the current models. However, in

addition to model deficiencies, this discrepancy may also be caused by artificially truncated EF distributions for observations where samples with bromine below DL were deleted from the data set, as explained in Sect. 2.4. In this regard, we note that some of the data sets reporting lowest median EFs for sea-salt size fractions (e.g. BEM97, HAW99, Figs. 2 and 4) correspond to those for which data below detection limits were retained without manipulation.

7. Laboratory Studies

Release of gas-phase bromine from aerosol is supported by several laboratory studies. Hirokawa et al. (1998) exposed ground NaBr salt in a reaction chamber to ozone and humidity. Using mass spectrometry they observed a release of bromine. Control experiments confirmed that both ozone and gaseous H_2O are necessary for the formation of Br_2. The presence or absence of irradiation (Xe arc lamp) made no difference in their study. They propose the reaction

$$O_3 + Br^- \xrightarrow{H^+} HOBr + O_2 \qquad (25)$$

as the first step in the formation of Br_2. According to Mochida et al. (2000), bromide in sea-salt is much more reactive than pure bromide. Anastasio and Mozurkewich (2002) found evidence for a glass-surface mediated bromide oxidation in the presence of ozone.

Disselkamp et al. (1999) let ozone flow through a solution containing NaBr and followed the acidity (ion-sensitive electrode) and the concentration of Br^- (ion chromatography). They found that H^+ and Br^- disappear at the same rate, which is consistent with reaction (25) followed by reaction (11). An enhanced bromide oxidation rate was observed when chloride was added to the solution. In that case Br^- and Cl^- disappeared at equal rates which is consistent with the formation of BrCl via reaction (12).

Behnke et al. (1999) generated sea-salt aerosol in a smog chamber and exposed it to ozone and light. From the observed fast decay of ozone they conclude that Br_2

and BrCl are produced. However, in contrast to Hirokawa et al. (1998), they observed a dependence on light intensity and claim that reaction (25) cannot be the (only) initiating step.

Abbatt and Waschewsky (1998) investigated the uptake of HOBr on NaCl solution in an aerosol kinetics flow tube. They obtained an uptake coefficient of $\gamma > 0.2$ for solutions of pH $\leq$ 7.2. For alkaline solution, the uptake was much slower. This is consistent with an acid-catalyzed reaction proceeding via Eq. (12).

Using a wetted-wall flow tube, Fickert et al. (1999) confirmed that a pH of 7 or less is necessary for uptake of HOBr on NaCl or NaBr solutions. Varying the composition of the solution they found, even with a molar $[Br^-]/[Cl^-]$ ratio below 1×10^{-3}, preferential formation of Br_2 relative to BrCl. Thus in the mbl, fresh aerosol particles with the sea water composition of $[Br^-]/[Cl^-] \approx 1.5\times10^{-3}$ mol/mol should lose Br^- preferentially over Cl^-.

8. Future projections

Based on current understanding of Br cycling through marine air, the projected increases in atmospheric acidification perhaps coupled with climatological alteration in global wind fields may lead to significant future changes in rates of Br activation and associated environmental impacts. Future increases in world population and per-capita energy use will almost certainly be associated with substantially increased emissions of SO_2, NO_x, and other acid precursors from fossil-fuel and biomass combustion and other activities (e.g. Galloway, 1996). The transport of increasing concentrations of these compounds and their reaction products over the oceans will in turn increase the rates and spatial extent of sea-salt aerosol acidification. Since ships emit substantial amounts of unregulated exhaust directly into the mbl (e.g. Capaldo et al., 1999), increasing ship traffic will likely contribute disproportionately to aerosol acidification of more remote regions of the mbl. Bromine activation is limited to acidic aerosol solutions and, consequently, increased acidification of marine air will lead to increased rates of

Br cycling. Since Br activation is relatively insensitive to pH variability in acidic aerosol, small to negligible influences are expected in polluted regions (such as the western North Atlantic Ocean) where most sea-salt aerosols are currently acidified within seconds to minutes anyway (e.g. Erickson et al., 1999). However, in more remote regions such as the high latitude southern oceans where Br activation may be limited by available acidity (e.g. Ayers et al., 1999), modest increases in acidification could lead to substantial increases in the rates, spatial extent, and seasonal duration of Br activation and cycling.

Potential modification in global wind fields associated with changes in Earth's climate would influence the distributions of atmospheric acidity via controls on long-distance transport as well as rates of air-sea exchange of both acid precursors (e.g. DMS) and bases (sea-salt alkalinity and NH_3). Changes in wind velocity would also alter the production fluxes, atmospheric concentrations, size distributions, and associated rates of multiphase transformations involving sea-salt Br. Since sea-salt production is a power function of wind velocity, relatively small changes in wind speed would have disproportionately large influences on sea-salt fluxes. Despite the dynamic and highly non-linear nature of the underlying processes, available evidence suggests that the temporal and spatial extent of active Br cycling will probably increase, particularly in more remote regions.

We thus see the need for additional field experiments, model studies, and laboratory investigations in the future. Simultaneous measurements of inorganic bromine in both phases, using all available techniques in one campaign (as well as obtaining auxiliary data like aerosol pH) would enhance our understanding a great deal. In particular, paired analyses of splits from size-segregated aerosol samples for total bromine (NAA or PIXE) and bromide (IC) would help elucidate the nature of bromine enrichments in submicrometer particles. Developing improved techniques to lower the DL for BrO would be particularly useful because the current DL is close to model-predicted concentrations. More measurements of bromine in mineral dust will help to better quantify its relevance as a source of bromine.

Future computer simulations should move from current box and one-dimensional (1D) to three-dimensional (3D) models. However, computing limitations do not allow the direct inclusion of full scale chemical mechanisms from the box models into global models. Therefore, a robust parameterisation of the halogen chemistry must be developed. Another aspect of future models will be explicit treatment of chemistry in size-resolved aerosols. In addition to sulfate and sea-salt aerosol, it will be necessary to consider the effect of other aerosol types like dust and soot on halogen chemistry.

Future laboratory studies are needed for the reaction of $BrNO_3$ with aerosol particles under conditions relevant to the mbl. Also, the conditions under which the slow aqueous-phase reaction of $O_3 + Br^-$ is accelerated in/on sea-salt aerosol (surface effects, light, catalysts, ...) should be investigated further.

9. Conclusions

Based upon a large number of observations, we come to the following conclusions:

- The main source of bromine in the mbl is sea salt. Other sources may contribute locally in some regions.
- Supermicrometer sea-salt aerosol is typically depleted in bromine. Compared to sea water, on average, about 50 % of the bromine is missing.
- Bromine depletions occur naturally in clean marine air as well as in anthropogenically influenced air.
- Acidity promotes aerosol debromination. However, although at least some acidity is required, the degree of debromination appears to be relatively insensitive to variability in the pH of acidic aerosol solutions.
- Marine submicrometer aerosol is often enriched in bromine, especially in polluted regions.

ACPD
3, 2963–3050, 2003

- Bromine from automobile petrol or biomass burning contributes in some regions to enrichment in submicrometer particles.
- A diurnal variation (with increased gas-phase concentrations and aerosol depletion during the day) has been observed at some, but not at all sites.
- Seasonal variation of EF is most pronounced in the cleaner southern hemisphere.
- Inorganic bromine species do exist in the gas phase at several pmol/mol but the speciation has not been reliably measured.
- EF in rain is higher than in aerosol particles, possibly because clouds and rain drops scavenge bromine species from the gas phase.
- Laboratory results show that aerosol bromide can be transformed into volatile, reactive forms of bromine.

Several questions remain:

- Which species comprise 'volatile inorganic bromine'?
- Why do some sites show a diurnal or seasonal variation of EF whereas others don't?
- Is there a vertical gradient of EF in the mbl?
- How can bromine accumulate in submicrometer particles instead of being recycled back into the gas phase?

Acknowledgements. For helpful discussions and for providing data we would like to thank Anne M. Johansen, Barbara J. Ray, Henning Rodhe, and Bill Sturges. Financial support for the University of Virginia was provided by the U.S. National Science Foundation (NSF) through grants ATM-9414293, ATM-941559, ATM-9634129, and ATM-9902077, the European Chemical Industry Council via Euro Chlor, and the Chemical Manufacturers' Association via the Chlorine

Chemical Council. Financial support for the Massachusetts Institute of Technology was provided by NSF grants ATM-9634129 and ATM-9902077 and NOAA award No. NA87RJ0445 via the Cooperative Institute for Climate and Ocean Research at the Woods Hole Oceanographic Institution. Financial support for Ghent University came from the Belgian Federal Office of Scientific, Technical and Cultural Affairs and the 'Fonds voor Wetenschappelijk Onderzoek – Vlaanderen'. N. Mihalopoulos and E. Baboukas wish to thank B. C. Nguyen and J. Sciare for providing the aerosol and rainwater samples and IPEV for logistical support.

References

Abbatt, J. P. D. and Waschewsky, G. C. G.: Heterogeneous interactions of HOBr, HNO_3, O_3, and NO_2 with deliquescent NaCl aerosols at room temperature, J. Phys. Chem. A, 102, 3719–3725, 1998. 3000

Adepetu, J. A., Asubiojo, O. I., Iskander, F. Y., and Bauer, T. L.: Elemental composition of Nigerian harmattan dust, J. Radioanal. Nucl. Chem., 121, 141–147, 1988. 2991

Alicke, B.: Messung von troposphärischen Halogenoxidradikalen in mittleren Breiten, Diplomarbeit, Ruprecht-Karls-Universität Heidelberg, Germany, 1997. 2989, 3029

Allan, B. J.: A spectroscopic study of radical chemistry in the troposphere, Ph.D. thesis, University of East Anglia, UK, 1998. 2989, 3029

Anastasio, C. and Mozurkewich, M.: Laboratory studies of bromide oxidation in the presence of ozone: Evidence for a glass-surface mediated reaction, J. Atmos. Chem., 41, 135–162, 2002. 2997, 2999

Anderson, J. P., Buseck, P. R., Patterson, T. L., and Arimoto, R.: Characterization of the Bermuda tropospheric aerosol by combined individual-particle and bulk-aerosol analysis, Atmos. Environ., 30, 319–338, 1996. 2981

Andreae, M. O.: Marine aerosol chemistry at Cape Grim, Tasmania, and Townsville, Queensland, J. Geophys. Res., 87C, 8875–8885, 1982. 2967, 3021

Andreae, M. O.: Climatic effects of changing atmospheric aerosol levels, in: World Survey of Climatology, Vol. 16, Future Climates of the World, edited by Henderson-Sellers, A., pp. 347–398, Elsevier, New York, 1995. 2968

Andreae, M. O. and Crutzen, P. J.: Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry, Science, 276, 1052–1058, 1997. 2998

Andreae, M. O., Atlas, E., Harris, G. W., Helas, G., de Kock, A., Koppmann, R., Maenhaut, W., Mano, S., Pollock, W. H., Rudolph, J., Scharffe, D., Schebeske, G., and Welling, M.: Methyl halide emissions from savanna fires in southern Africa, J. Geophys. Res., 101D, 23 603–23 613, 1996. 2992

Andreae, M. O., Andreae, T. W., Annegarn, H., Beer, J., Cachier, H., le Canut, P., Elbert, W., Maenhaut, W., Salma, I., Wienhold, F. G., and Zenker, T.: Airborne studies of aerosol emissions from savanna fires in southern Africa: 2. Aerosol chemical composition, J. Geophys. Res., 103D, 32 119–32 128, 1998. 2992, 3032

Arimoto, R., Duce, R. A., Ray, B. J., Hewitt, A. D., and Williams, J.: Trace elements in the atmosphere of American Samoa: Concentrations and deposition to the tropical South Pacific, J. Geophys. Res., 92D, 8465–8479, 1987. 2967, 3024

Arimoto, R., Ray, B. J., Duce, R. A., Hewitt, A. D., Boldi, R., and Hudson, A.: Concentrations, sources, and fluxes of trace elements in the remote marine atmosphere of New Zealand, J. Geophys. Res., 95D, 22 389–22 405, 1990. 3023

Arimoto, R., Duce, R. A., Ellis, Jr., W. G., Cullen, J. D., and Merrill, J. T.: Trace elements in the atmosphere over the North Atlantic, J. Geophys. Res., 100D, 1199–1213, 1995. 3020, 3023, 3025

Ayers, G. P., Gillett, R. W., Cainey, J. M., and Dick, A. L.: Chloride and bromide loss from seasalt particles in southern ocean air, J. Atmos. Chem., 33, 299–319, 1999. 2967, 2970, 2984, 2985, 2986, 3001, 3021, 3023, 3026, 3030

Baboukas, E.: *Χωρική, εποχική και διαχρονική διακύμανση όξινων και αλκαλικών υδατοδιαλυτών συστατικών στην ατμόσφαιρα του νότιου Ινδικού Ωκεανού: νησιά* Amsterdam, Crozet *και* Kerguelen (Spatial, temporal, and interannual variability of water soluble species in aerosols, gases and precipitation in the Southern Indian Ocean: Amsterdam, Crozet and Kerguelen islands), Ph.D. thesis, University of Crete, Greece, 2000. 2984, 2985, 3020, 3021, 3030, 3031

Baboukas, E. D., Kanakidou, M., and Mihalopoulos, N.: Carboxylic acids in gas and particulate phase above the Atlantic Ocean, J. Geophys. Res., 105D, 14 459–14 471, 2000. 3020

Barrie, L. A., Bottenheim, J. W., Schnell, R. C., Crutzen, P. J., and Rasmussen, R. A.: Ozone destruction and photochemical reactions at polar sunrise in the lower Arctic atmosphere, Nature, 334, 138–141, 1988. 2966

Behne, W.: Untersuchungen zur Geochemie des Chlor und Brom, Geochim. Cosmochim. Acta, 3, 186–214, 1953. 2966

Behnke, W., Scheer, V., and Zetzsch, C.: Production of $BrNO_2$, Br_2 and $ClNO_2$ from the reaction between sea spray aerosol and N_2O_5, J. Aerosol Sci., 25, S277–S278, 1994. 2972, 2995, 2997

Behnke, W., Elend, M., Krüger, U., and Zetzsch, C.: The influence of NaBr/NaCl ratio on the Br^--catalyzed production of halogenated radicals, J. Atmos. Chem., 34, 87–99, 1999. 2999

Berg, W. W. and Winchester, J. W.: Aerosol chemistry of the marine atmosphere, in: Chemical Oceanography, Vol. 7, 2nd Ed., edited by Riley, J. P. and Chester, R., pp. 173–231, Academic Press, 1978. 2966, 2972

Berg, W. W., Grahek, F. E., Gladney, E. S., and Sedlacek, W. A.: The global bromine budget: Recent measurements and theories, in: Proc. 2nd Symposium on the Nonurban Atmosphere, pp. 72–75, American Meteorological Society, Williamsburg, 1982. 3027

Berg, W. W., Sperry, P. D., Rahn, K. A., and Gladney, E. S.: Atmospheric bromine in the Arctic, J. Geophys. Res., 88C, 6719–6736, 1983. 2977, 2983

Blanchard, D. C., Woodward, A. H., and Cipriano, R. J.: The vertical distribution of the concentration of sea salt in the marine atmosphere near Hawaii, Tellus, 36B, 118–125, 1984. 2969

Boucher, O., Moulin, C., Belviso, S., Aumont, O., Bopp, L., Cosme, E., von Kuhlmann, R., Lawrence, M. G., Pham, M., Reddy, M. S., Sciare, J., and Venkataraman, C.: Sensitivity study of dimethylsulphide (DMS) atmospheric concentrations and sulphate aerosol indirect radiative forcing to the DMS source representation and oxidation, Atmos. Chem. Phys., 3, 49–65, 2003. 2998

Capaldo, K., Corbett, J. J., Kasibhatla, P., Fischbeck, P., and Pandis, S. N.: Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean, Nature, 400, 743–746, 1999. 3000

Chance, K.: Analysis of BrO measurements from the global ozone monitoring experiment, Geophys. Res. Lett., 25, 3335–3338, 1998. 2988, 3028

Cicerone, R. J.: Halogens in the atmosphere, Rev. Geophys. Space Phys., 19, 123–139, 1981. 2966

Dentener, F. J., Carmichael, G. R., Zhang, Y., Lelieveld, J., and Crutzen, P. J.: Role of mineral aerosol as a reactive surface in the global troposphere, J. Geophys. Res., 101D, 22 869–22 889, 1996. 2981, 2991

Dickerson, R. R., Rhoads, K. P., Carsey, T. P., Oltmans, S. J., Burrows, J. P., and Crutzen, P. J.: Ozone in the remote marine boundary layer: A possible role for halogens, J. Geophys. Res.,

104D, 21 385–21 395, 1999. 2987
Disselkamp, R. S., Chapman, E. G., Barchet, W. R., Colson, S. D., and Howd, C. D.: BrCl production in NaBr/NaCl/HNO_3/O_3 solutions representative of sea-salt aerosols in the marine boundary layer, Geophys. Res. Lett., 26, 2183–2186, 1999. 2999
Duce, R. A. and Hoffman, E.: Chemical fractionation at the air/sea interface, Annu. Rev. Earth Planet. Sci., 4, 187–228, 1976. 2966, 2971
Duce, R. A. and Woodcock, A. H.: Difference in chemical composition of atmospheric sea salt particles produced in the surf zone and on the open sea in Hawaii, Tellus, 23, 427–435, 1971. 2971, 2982, 3022
Duce, R. A., Wasson, J. T., Winchester, J. W., and Burns, F.: Atmospheric iodine, bromine, and chlorine, J. Geophys. Res., 68, 3943–3947, 1963. 2966, 3022, 3030
Duce, R. A., Winchester, J. W., and van Nahl, T. W.: Iodine, bromine, and chlorine in the Hawaiian marine atmosphere, J. Geophys. Res., 70, 1775–1799, 1965. 2967, 2977, 2982, 2993, 3022, 3027, 3030
Duce, R. A., Woodcock, A. H., and Moyers, J. L.: Variation of ion ratios with size among particles in tropical oceanic air, Tellus, 19, 369–379, 1967. 2978, 3022
Duce, R. A., Arimoto, R., Ray, B. J., Unni, C. K., and Harder, P. J.: Atmospheric trace elements at Enewetak Atoll: 1, Concentrations, sources, and temporal variability, J. Geophys. Res., 88C, 5321–5342, 1983. 2994, 3022
Duce, R. A., Liss, P. S., Merrill, J. T., Atlas, E. L., Buat-Menard, P., Hicks, B. B., Miller, J. M., Prospero, J. M., Arimoto, R., Church, T. M., Ellis, W., Galloway, J. N., Hansen, L., Jickells, T. D., Knap, A. H., Reinhardt, K. H., Schneider, B., Soudine, A., Tokos, J. J., Tsunogai, S., Wollast, R., and Zhao, M.: The atmospheric input of trace species to the world oceans, Global Biogeochem. Cycles, 5, 193–259, 1991. 2991
Echalar, F., Gaudichet, F., Cachier, H., and Artaxo, P.: Aerosol emissions by tropical forest and savanna biomass burning: Characteristic trace elements and fluxes, Geophys. Res. Lett., 22, 3039–3042, 1995. 2992
Erickson, III, D. J., Seuzaret, C., Keene, W. C., and Gong, S. L.: A general circulation model based calculation of HCl and $ClNO_2$ production from sea-salt dechlorination: Reactive chlorine emissions inventory, J. Geophys. Res., 104D, 8347–8372, 1999. 2969, 2979, 2987, 2990, 3001
Fan, S.-M. and Jacob, D. J.: Surface ozone depletion in Arctic spring sustained by bromine reactions on aerosols, Nature, 359, 522–524, 1992. 2996

Fickert, S., Adams, J. W., and Crowley, J. N.: Activation of Br_2 and BrCl via uptake of HOBr onto aqueous salt solutions, J. Geophys. Res., 104D, 23 719–23 727, 1999. 3000
Finlayson-Pitts, B. J. and Johnson, S. N.: The reaction of NO_2 with NaBr: Possible source of BrNO in polluted marine atmospheres, Atmos. Environ., 22, 1107–1112, 1988. 2995
Finlayson-Pitts, B. J., Livingston, F. E., and Berko, H. N.: Ozone destruction and bromine photochemistry at ground level in the Arctic spring, Nature, 343, 622–625, 1990. 2995, 2997
Foster, K. L., Plastridge, R. A., Bottenheim, J. W., Shepson, P. B., Finlayson-Pitts, B. J., and Spicer, C. W.: The role of Br_2 and BrCl in surface ozone destruction at polar sunrise, Science, 291, 471–474, 2001. 3027
François, F. and Maenhaut, W.: Chemical composition and sources of the size-fractionated atmospheric aerosol collected at the research platform Nordsee, in: Proceedings of EUROTRAC Symposium '94, edited by Borrell, P. M., Borrell, P., Cvitaš, T., and Seiler, W., pp. 472–476, SPB Academic Publishing bv, The Hague, 1994. 2982, 3023, 3025
François, F., Cafmeyer, J., Gilot, C., and Maenhaut, W.: Chemical composition of size-fractionated atmospheric aerosols at some coastal stations and over the North Sea, in: Proceedings of EUROTRAC Symposium '92, edited by Borrell, P. M., Borrell, P., Cvitaš, T., and Seiler, W., pp. 788–791, SPB Academic Publishing bv, The Hague, 1993. 3023, 3025
Friess, U., Otten, C., Chipperfield, M., Wagner, T., Pfeilsticker, K., and Platt, U.: Intercomparison of measured and modelled BrO slant column amounts for the Arctic winter and spring 1994/95, Geophys. Res. Lett., 26, 1861–1864, 1999. 2989
Frigge, M., Hoaglin, D. C., and Iglewicz, B.: Some implementations of the boxplot, Am. Stat., 43, 50–54, 1989. 3035
Gabriel, R., von Glasow, R., Sander, R., Andreae, M. O., and Crutzen, P. J.: Bromide content of sea-salt aerosol particles collected over the Indian Ocean during INDOEX 1999, J. Geophys. Res., 107D, 8032, 10.1029/2001JD001 133, 2002. 2994, 3023
Galbally, I. E., Bentley, S. T., and Meyer, C. P.: Mid-latitude marine boundary-layer ozone destruction at visible sunrise observed at Cape Grim, Tasmania, 41°S, Geophys. Res. Lett., 27, 3841–3844, 2000. 2988
Galloway, J. N.: Anthropogenic mobilization of sulphur and nitrogen: Immediate and delayed consequences, Annu. Rev. Energy Environ., 21, 261–292, 1996. 3000
Galloway, J. N., Likens, G. E., Keene, W. C., and Miller, J. M.: The composition of precipitation in remote areas of the world, J. Geophys. Res., 87C, 8771–8786, 1982. 2967
Gard, E. E., Kleeman, M. J., Gross, D. S., Hughes, L. S., Allen, J. O., Morrical, B. D., Fergenson,

D. P., Dienes, T., Gälli, M. E., Johnson, R. J., Cass, G. R., and Prather, K. A.: Direct observation of heterogeneous chemistry in the atmosphere, Science, 279, 1184–1187, 1998. 2968
Gong, S. L., Barrie, L. A., and Blanchet, J.-P.: Modeling sea-salt aerosols in the atmosphere: 1. Model development, J. Geophys. Res., 102D, 3805–3818, 1997. 2969, 2987
Graedel, T. E. and Keene, W. C.: The tropospheric budget of reactive chlorine, Global Biogeochem. Cycles, 9, 47–77, 1995. 2968
Granat, L., Norman, M., Leck, C., Kulshrestha, U. C., and Rodhe, H.: Wet scavenging of sulfur compounds and other constituents during the Indian Ocean Experiment (INDOEX), J. Geophys. Res., 107D, 10.1029/2001JD000 499, 2002. 3031
Grewe, V. and Dameris, M.: Calculating the global mass exchange between stratosphere and troposphere, Ann. Geophys., 14, 431–442, 1996. 2994
Habibi, K.: Characterization of particulate matter in vehicle exhaust, Environ. Sci. Technol., 7, 223–234, 1973. 2993
Hamilton, B.: Gasoline FAQ, http://www.faqs.org/faqs/autos/gasoline-faq/, 1996. 2993
Hansson, H.-C. and Nyman, S.: Microcomputer-controlled two size fractionating aerosol sampler for outdoor environments, Environ. Sci. Technol., 19, 1110–1115, 1985. 3025
Harder, H., Bösch, H., Camy-Peyret, C., Chipperfield, M. P., Fitzenberger, R., Payan, S., Perner, D., Platt, U., Sinnhuber, B.-M., and Pfeilsticker, K.: Comparison of measured and modeled stratospheric BrO: Implications for the total amount of stratospheric bromine, Geophys. Res. Lett., 27, 3695–3698, 2000. 2989
Harrison, R. M. and Sturges, W. T.: The measurement and interpretation of Br/Pb ratios in airborne particles, Atmos. Environ., 17, 311–328, 1983. 2993, 2994
Hebestreit, K., Stutz, J., Rosen, D., Matveiv, V., Luria, M., and Platt, U.: DOAS measurements of tropospheric bromine oxide in mid-latitudes, Science, 283, 55–57, 1999. 2966, 2972, 2988, 3029
Hegels, E., Crutzen, P. J., Klüpfel, T., and Perner, D.: Global distribution of atmospheric bromine-monoxide from GOME on earth observing satellite ERS-2, Geophys. Res. Lett., 25, 3127–3130, 1998. 2988, 3028
Hirokawa, J., Onaka, K., Kajii, Y., and Akimoto, H.: Heterogeneous processes involving sodium halide particles and ozone: Molecular bromine release in the marine boundary layer in the absence of nitrogen oxides, Geophys. Res. Lett., 25, 2449–2452, 1998. 2997, 2999, 3000
Hönninger, G.: Referenzspektren reaktiver Halogenverbindungen für DOAS-Messungen, Diplomarbeit, Ruprecht-Karls-Universität Heidelberg, Germany, http://www.iup.

uni-heidelberg.de/urmel/abstracts/tit2hg.html, 1999. 2989, 3029
Hönninger, G.: Halogen Oxide Studies in the Boundary Layer by Multi Axis Differential Optical Absorption Spectroscopy and Active Longpath-DOAS, Ph.D. thesis, Universität Heidelberg, Institut für Umweltphysik, http://www.ub.uni-heidelberg.de/archiv/1940, 2002. 2973, 2989, 3028
Hönninger, G. and Platt, U.: Observations of BrO and its vertical distribution during surface ozone depletion at Alert, Atmos. Environ., 36, 2481–2489, 2002. 2973
Howell, S., Pszenny, A. A. P., Quinn, P., and Huebert, B. J.: A field intercomparison of three cascade impactors, Aerosol Sci. Technol., 29, 475–492, 1998. 3024
Huang, S., Arimoto, R., and Rahn, K. A.: Changes in atmospheric lead and other pollution elements at Bermuda, J. Geophys. Res., 101D, 21 033–21 040, 1996. 2994
Huebert, B. J., Lee, G., and Warren, W. L.: Airborne aerosol inlet passing efficiency measurement, J. Geophys. Res., 95D, 16 369–16 381, 1990. 2968
Impey, G. A., Shepson, P. B., Hastie, D. R., Barrie, L. A., and Anlauf, K. G.: Measurements of photolyzable chlorine and bromine during the Polar Sunrise Experiment 1995, J. Geophys. Res., 102D, 16 005–16 010, 1997. 2973
James, J. D., Harrison, R. M., Savage, N. H., Allen, A. G., Grenfell, J. L., Allan, B. J., Plane, J. M. C., Hewitt, C. N., Davison, B., and Robertson, L.: Quasi-Lagrangian investigation into dimethyl sulfide oxidation in maritime air using a combination of measurements and model, J. Geophys. Res., 105D, 26 379–26 392, 2000. 3029
Jayne, J. T., Leard, D. C., Zhang, X., Davidovits, P., Smith, K. A., Kolb, C., and Worsnop, D. R.: Development of an aerosol mass spectrometer for size and composition analysis of submicron particles, Aerosol Sci. Technol., 33, 49–70, 2000. 2968
Jernigan, E. L., Ray, B. J., and Duce, R. A.: Lead and bromine in atmospheric particulate matter on Oahu, Hawaii, Atmos. Environ., 5, 881–886, 1971. 2993
Jobson, B. T., Niki, H., Yokouchi, Y., Bottenheim, J., Hopper, F., and Leaitch, R.: Measurements of C_2-C_6 hydrocarbons during the polar sunrise 92 experiment: Evidence for Cl-atom and Br-atom chemistry, J. Geophys. Res., 99D, 25 355–25 368, 1994. 2973
Johansen, A. M., Siefert, R. L., and Hoffmann, M. R.: Chemical characterization of ambient aerosol collected during the southwest monsoon and intermonsoon seasons over the Arabian Sea: Anions and cations, J. Geophys. Res., 104D, 26 325–26 347, 1999. 3020
Johansen, A. M., Siefert, R. L., and Hoffmann, M. R.: Chemical composition of aerosols collected over the tropical North Atlantic Ocean, J. Geophys. Res., 105D, 15 277–15 312, 2000.

3020
Keene, W. C. and Savoie, D. L.: The pH of deliquesced sea-salt aerosol in polluted marine air, Geophys. Res. Lett., 25, 2181–2184, 1998. 2969, 2975, 3021
Keene, W. C. and Savoie, D. L.: Correction to "The pH of deliquesced sea-salt aerosol in polluted marine air", Geophys. Res. Lett., 26, 1315–1316, 1999. 2969, 3021
Keene, W. C., Pszenny, A. A. P., Galloway, J. N., and Hawley, M. E.: Sea-salt corrections and interpretation of constituent ratios in marine precipitation, J. Geophys. Res., 91D, 6647–6658, 1986. 2970
Keene, W. C., Pszenny, A. A. P., Jacob, D. J., Duce, R. A., Galloway, J. N., Schultz-Tokos, J. J., Sievering, H., and Boatman, J. F.: The geochemical cycle of reactive chlorine through the marine troposphere, Global Biogeochem. Cycles, 4, 407–430, 1990. 2970, 2987
Keene, W. C., Sander, R., Pszenny, A. A. P., Vogt, R., Crutzen, P. J., and Galloway, J. N.: Aerosol pH in the marine boundary layer: A review and model evaluation, J. Aerosol Sci., 29, 339–356, 1998. 2969, 2986
Keene, W. C., Khalil, M. A. K., Erickson, III, D. J., McCulloch, A., Graedel, T. E., Lobert, J. M., Aucott, M. L., Gong, S. L., Harper, D. B., Kleiman, G., Midgley, P., Moore, R. M., Seuzaret, C., Sturges, W. T., Benkovitz, C. M., Koropalov, V., Barrie, L. A., and Li, Y. F.: Composite global emissions of reactive chlorine from anthropogenic and natural sources: Reactive chlorine emissions inventory, J. Geophys. Res., 104D, 8429–8440, 1999. 2992
Keene, W. C., Pszenny, A. A. P., Maben, J. R., and Sander, R.: Variation of marine aerosol acidity with particle size, Geophys. Res. Lett., 29, 10.1029/2001GL013 881, 2002. 2969, 2975, 2980, 3021
Khalil, M. A. K., Rasmussen, R. A., and Gunawardena, R.: Atmospheric methyl bromide: Trends and global mass balance, J. Geophys. Res., 98D, 2887–2896, 1993. 2994
Kleeman, M. J., Schauer, J. J., and Cass, G. R.: Size and composition distribution of fine particulate matter emitted from wood burning, meat charbroiling, and cigarettes, Environ. Sci. Technol., 33, 3516–3523, 1999. 2992
Kouvarakis, G., Doukelis, Y., Mihalopoulos, N., Rapsomanikis, S., Sciare, J., and Blumthaler, M.: Chemical, physical and optical characterization of aerosols during PAUR II experiment, J. Geophys. Res., 107D, 10.1029/2000JD000 291, 2002. 3021
Kritz, M. A. and Rancher, J.: Circulation of Na, Cl, and Br in the tropical marine atmosphere, J. Geophys. Res., 85C, 1633–1639, 1980. 2967, 3020, 3027
Leser, H., Platt, U., and Hönninger, G.: MAX-DOAS Measurements of BrO and NO_2 in the

marine boundary layer, Geophys. Res. Lett., (in press), 2003. 2973, 2989, 3028
Li, S.-M., Yokouchi, Y., Barrie, L. A., Muthuramu, K., Shepson, P. B., Bottenheim, J. W., Sturges, W. T., and Landsberger, S.: Organic and inorganic bromine compounds and their composition in the Arctic troposphere during polar sunrise, J. Geophys. Res., 99D, 25 415–25 428, 1994. 2972
Li-Jones, X., Maring, H. B., and Prospero, J. M.: Effect of relative humidity on light scattering by mineral dust aerosol as measured in the marine boundary layer over the tropical Atlantic Ocean, J. Geophys. Res., 103D, 31 113–31 121, 1998. 2991
Lininger, R. L., Duce, R. A., Winchester, J. W., and Matson, W. R.: Chlorine, bromine, iodine, and lead in aerosols from Cambridge, Massachusetts, J. Geophys. Res., 71, 2457–2463, 1966. 2993
Maenhaut, W., Darzi, M., and Winchester, J. W.: Seawater and nonseawater aerosol components in the marine atmosphere of Samoa, J. Geophys. Res., 86C, 3187–3193, 1981a. 3024
Maenhaut, W., Selen, A., van Espen, P., van Grieken, R., and Winchester, J. W.: PIXE analysis of aerosol samples collected over the Atlantic Ocean from a sailboat, Nucl. Instrum. Methods, 181, 399–405, 1981b. 3020
Maenhaut, W., Raemdonck, H., Selen, A., van Grieken, R., and Winchester, J. W.: Characterization of the atmospheric aerosol over the eastern equatorial Pacific, J. Geophys. Res., 88C, 5353–5364, 1983. 3020, 3024
Maenhaut, W., François, F., Cafmeyer, J., Gilot, C., and Hanssen, J. E.: Long-term aerosol study in southern Norway, and the relationship of aerosol components to source regions, in: Proceedings of EUROTRAC Symposium '96, edited by Borrell, P. M., Borrell, P., Kelly, K., and Seiler, W., pp. 277–280, SPB Academic Publishing bv, The Hague, 1996a. 3021
Maenhaut, W., Salma, I., Cafmeyer, J., Annegarn, H. J., and Andreae, M. O.: Regional atmospheric aerosol composition and sources in the eastern Transvaal, South Africa, and impact of biomass burning, J. Geophys. Res., 101D, 23 631–23 650, 1996b. 2992, 3032
Maenhaut, W., Fernández-Jiménez, M.-T., Vanderzalm, J. L., Hooper, B., Hooper, M. A., and Tapper, N. J.: Aerosol composition at Jabiru, Australia, and impact of biomass burning, J. Aerosol Sci., 31, S745–S746, 2000. 3023
Mamou, A., Rabani, J., and Behar, D.: On the oxidation of aqueous Br^- by OH radicals, studied by pulse radiolysis, J. Phys. Chem., 81, 1447–1448, 1977. 2997
Marchand, M. E.: Sur la constitution physique et chimique des eaux naturelles, C. R. Hebd.

Seances Acad. Sci., 34, 54–56, 1852. 2966
Martens, C. S.: Ion ratio variations with particle size in Puerto Rican aerosols, J. Geophys. Res., 78, 8867–8871, 1973. 2993, 3024
Martens, C. S. and Harriss, R. C.: Chemistry of aerosols, cloud droplets, and rain in the Puerto Rican marine atmosphere, J. Geophys. Res., 78, 949–957, 1973. 3031
Martinez, M., Arnold, T., and Perner, D.: The role of bromine and chlorine chemistry for Arctic ozone depletion events in Ny Ålesund and comparison with model calculations, Ann. Geophys., 17, 941–956, 1999. 2972
Mason, B. and Moore, C. B.: Principles of Geochemistry, fourth edition, John Wiley & Sons, Inc., 1982. 3032
Matveev, V., Peleg, M., Rosen, D., Tov-Alper, D. S., Hebestreit, K., Stutz, J., Platt, U., Blake, D., and Luria, M.: Bromine oxide - ozone interaction over the Dead Sea, J. Geophys. Res., 106D, 10 375–10 387, 2001. 2988, 3029
McKenzie, L. M., Ward, D. E., and Hao, W. M.: Chlorine and bromine in the biomass of tropical and temperate ecosystems, in: Biomass Burning and Global Change, Vol. 1, Remote Sensing, Modeling and Inventory Development, and Biomass Burning in Africa, edited by Levine, J. S., pp. 241–248, The MIT press, Cambridge, Massachusetts, USA, 1996. 2992, 3032
Middlebrook, A. M., Murphy, D. M., and Thomson, D. S.: Observations of organic material in individual marine particles at Cape Grim during the first Aerosol Characterization Experiment (ACE 1), J. Geophys. Res., 103D, 16 475–16 483, 1998. 2981
Mihalopoulos, N., Stephanou, E., Kanakidou, M., Pilitsidis, S., and Bousquet, P.: Tropospheric aerosol ionic composition in the Eastern Mediterranean region, Tellus, 49B, 314–326, 1997. 3021
Mochida, M., Hirokawa, J., and Akimoto, H.: Unexpected large uptake of O_3 on sea salts and the observed Br_2 formation, Geophys. Res. Lett., 27, 2629–2632, 2000. 2999
Moldanová, J. and Ljungström, E.: Sea-salt aerosol chemistry in coastal areas: A model study, J. Geophys. Res., 106D, 1271–1296, 2001. 2978
Moortgat, G. K., Meller, R., and Schneider, W.: Temperature dependence (256-296 K) of the absorption cross-sections of bromoform in the wavelength range 285-360 nm, in: The Tropospheric Chemistry of Ozone in the Polar Regions, NATO ASI Series, Vol. I7, edited by Niki, H. and Becker, K. H., pp. 359–369, Springer Verlag, Berlin, 1993. 2998
Moyers, J. L. and Duce, R. A.: Gaseous and particulate bromine in the marine atmosphere, J. Geophys. Res., 77, 5330–5338, 1972. 2972, 2983, 3022, 3027

Moyers, J. L., Zoller, W. H., Duce, R. A., and Hoffman, G. L.: Gaseous bromine and particulate lead, vanadium, and bromine in a polluted atmosphere, Environ. Sci. Technol., 6, 68–71, 1972. 2993

Mozurkewich, M.: Mechanisms for the release of halogens from sea-salt particles by free radical reactions, J. Geophys. Res., 100D, 14 199–14 207, 1995. 2996, 2998

Murphy, D. M., Thomson, D. S., and Middlebrook, A. M.: Bromine, iodine, and chlorine in single aerosol particles at Cape Grim, Geophys. Res. Lett., 24, 3197–3200, 1997. 2968, 2978, 2985, 3021

Nagao, I., Matsumoto, K., and Tanaka, H.: Sunrise ozone destruction found in the sub-tropical marine boundary layer, Geophys. Res. Lett., 26, 3377–3380, 1999. 2987

Nishri, A. and Stiller, M.: Iron, Magnesese, and Trace Elements in the Dead Sea, in: The Dead Sea and its Setting, edited by T.M. Niemi, Z. Ben-Avraham and J.R. Gat, pp. 199–204, Oxford University Press, New York, Oxford, 1997. 2988

Nowak, J. B., Davis, D. D., Chen, G., Eisele, F. L., Mauldin III, R. L., Tanner, D. J., Cantrell, C., Kosciuch, E., Bandy, A., Thornton, D., and Clarke, A.: Airborne observations of DMSO, DMS, and OH at marine tropical latitudes, Geophys. Res. Lett., 28, 2201–2204, 2001. 2988

Oum, K. W., Lakin, M. J., and Finlayson-Pitts, B. J.: Bromine activation in the troposphere by the dark reaction of O_3 with seawater ice, Geophys. Res. Lett., 25, 3923–3926, 1998. 2997

Perner, D., Crutzen, P. J., von Glasow, R., Klüpfel, T., Martinez, M., Sander, R., and Keene, W. C.: Halogen oxides above the Pacific Ocean, Eos, Trans. AGU (Abstract Supplement), 81/48, F165, 2000. 3027

Phillips, C. A., Howell, S. G., Huebert, B. J., and Zhuang, L.: Bromide in the remote marine boundary layer, Eos, Trans. AGU (Abstract Supplement), 81/48, F151, 2000. 3022

Prospero, J. M., Barrett, K., Church, T., Dentener, F., Duce, R. A., Galloway, J. N., Levy II, H., Moody, J., and Quinn, P.: Atmospheric deposition of nutrients to the North Atlantic basin, Biogeochem., 35, 27–73, 1996. 2990, 2991

Pszenny, A., Fischer, C., Mendez, A., and Zetwo, M.: Direct comparison of cellulose and quartz fiber filters for sampling submicrometer aerosols in the marine boundary layer, Atmos. Environ., 27A, 281–284, 1993. 3024

Pszenny, A. A. P.: Atmospheric deposition of nitrate to the ocean surface, Ph.D. thesis, University of Rhode Island, Kingston, 1987. 3023, 3024, 3030, 3031

Pszenny, A. A. P.: Particle size distributions of methanesulfonate in the tropical Pacific marine boundary layer, J. Atmos. Chem., 14, 273–284, 1992. 3024

Pszenny, A. A. P., MacIntyre, F., and Duce, R. A.: Sea-salt and the acidity of marine rain on the windward coast of Samoa, Geophys. Res. Lett., 9, 751–754, 1982. 3031
Pszenny, A. A. P., Castelle, A. J., Galloway, J. N., and Duce, R. A.: A study of the sulfur cycle in the Antarctic marine boundary layer, J. Geophys. Res., 94, 9818–9830, 1989. 2975, 3024
Pundt, I., van Roozendael, M., Wagner, T., Richter, A., Chipperfield, M. P., Burrows, J. P., Fayt, C., Hendrick, F., Pfeilsticker, K., Platt, U., and Pommereau, J. P.: Simultaneous UV-vis Measurements of BrO from Balloon, Satellite and Ground: Implications for Tropospheric BrO, in: Air Pollution Research Report 73, Proc. 5th European Symposium on Polar Stratospheric Ozone 1999, CEC, edited by Harris, N. R. P., Guirlet, M., and Amanatis, G. T., pp. 316–319, 2000. 2989, 3029
Quack, B. and Wallace, D. W. R.: Air-sea flux of bromoform: Controls, rates, and implications, Global Biogeochem. Cycles, 17, 10.1029/2002GB001 890, 2003. 2994
Rader, D. J. and Marple, V. A.: A study of the effects of anisokinetic sampling, Aerosol Sci. Technol., 8, 283–299, 1988. 2968
Raemdonck, H., Maenhaut, W., and Andreae, M. O.: Chemistry of marine aerosol over the tropical and equatorial Pacific, J. Geophys. Res., 91D, 8623–8636, 1986. 2967, 3024
Rahn, K. A., Borys, R. D., and Duce, R. A.: Tropospheric halogen gases: Inorganic and organic components, Science, 192, 549–550, 1976. 2972, 3027
Rancher, J. and Kritz, M. A.: Diurnal fluctuations of Br and I in the tropical marine atmosphere, J. Geophys. Res., 85C, 5581–5587, 1980. 2983, 2984, 3020
Richter, A., Wittrock, F., Eisinger, M., and Burrows, J. P.: GOME observations of tropospheric BrO in northern hemispheric spring and summer 1997, Geophys. Res. Lett., 25, 2683–2686, 1998. 2988, 3028
Rudich, Y., Talukdar, R. K., and Ravishankara, A. R.: Multiphase chemistry of NO_3 in the remote troposphere, J. Geophys. Res., 103D, 16 133–16 143, 1998. 2997
Sadasivan, S.: Trace elements in size separated aerosols over sea, Atmos. Environ., 12, 1677–1683, 1978. 3022
Sadasivan, S.: Trace constituents in cloud water, rainwater and aerosol samples collected near the west coast of India during the southwest monsoon, Atmos. Environ., 14, 33–38, 1980. 2978, 3022, 3031
Sadasivan, S. and Anand, S. J. S.: Chlorine, bromine and iodine in monsoon rains in India, Tellus, 31, 290–294, 1979. 3030
Saito, K., Muto, H., Takizama, Y., and Kodama, M.: Concentrations of various elements and

inorganic ions in rice straw and ash, Toxicol. Environ. Chem., 41, 15–20, 1994. 3032
Sander, R.: Compilation of Henry's law constants for inorganic and organic species of potential importance in environmental chemistry (version 3), http://www.mpch-mainz.mpg.de/~sander/res/henry.html, 1999. 2995
Sander, R. and Crutzen, P. J.: Model study indicating halogen activation and ozone destruction in polluted air masses transported to the sea, J. Geophys. Res., 101D, 9121–9138, 1996. 2970, 2972, 2996, 2997
Sander, R., Rudich, Y., von Glasow, R., and Crutzen, P. J.: The role of $BrNO_3$ in marine tropospheric chemistry: A model study, Geophys. Res. Lett., 26, 2857–2860, 1999. 2972, 2997
Schauffler, S. M., Atlas, E. L., Flocke, F., Leub, R. A., Stroud, V., and Travnicek, W.: Measurements of bromine-containing organic compounds at the tropical tropopause, Geophys. Res. Lett., 25, 317–320, 1998. 2994
Schütz, L. and Rahn, K.: Trace-element concentrations in erodible soils, Atmos. Environ., 16, 171–176, 1982. 2990
Sciare, J., Baboukas, E., Kanakidou, M., Krischke, U., Belviso, S., Bardouki, H., and Mihalopoulos, N.: Spatial and temporal variability of atmospheric sulfur-containing gases and particles during the Albatross campaign, J. Geophys. Res., 105D, 14 433–14 448, 2000. 2988
Seto, Y.-B., Duce, R. A., and Woodcock, A. H.: Sodium-to-chlorine ratio in Hawaiian rains as a function of distance inland and of elevation, J. Geophys. Res., 74, 1101–1103, 1969. 3030
Slocum, D. H., McGinnes, Jr., E. A., and McKown, D. M.: Elemental analysis of oak and hickory charcoal using neutron activation analysis, Wood Fiber, 10, 200–209, 1978. 3032
Spicer, C. W., Chapman, E. G., Finlayson-Pitts, B. J., Plastridge, R. A., Hubbe, J. M., Fast, J. D., and Berkowitz, C. M.: Unexpectedly high concentrations of molecular chlorine in coastal air, Nature, 394, 353–356, 1998. 2972, 3027
Stumm, W. and Brauner, P. A.: Chemical Speciation, in: Chemical Oceanography, Vol. 1, 2nd Ed., edited by Riley, J. P. and Skirrow, G., pp. 173–239, Academic Press, 1975. 2968
Sturges, W. T.: Excess particulate and gaseous bromine at a remote coastal location, Atmos. Environ., 24A, 167–171, 1990. 2993, 3022, 3027
Sturges, W. T. and Harrison, R. M.: Bromine:lead ratios in airborne particles from urban and rural sites, Atmos. Environ., 20, 577–588, 1986a. 3023
Sturges, W. T. and Harrison, R. M.: Bromine in marine aerosols and the origin, nature and quantity of natural atmospheric bromine, Atmos. Environ., 20, 1485–1496, 1986b. 2966,

2993, 3023, 3027
Sturges, W. T., Harrison, R. M., and Dams, R.: Development of a technique for the determination of lead and bromine in atmospheric particles by X-ray fluorescence, Atmos. Environ., 19, 1495–1502, 1985. 2967
Stutz, J., Ackermann, R., Fast, J. D., and Barrie, L.: Atmospheric reactive chlorine and bromine at the Great Salt Lake, Utah, Geophys. Res. Lett., 29, 10.1029/2002GL014 812, 2002. 2988, 3028
Swap, R., Garstang, M., Greco, S., Talbot, R., and Kallberg, P.: Saharan dust in the Amazon basin, Tellus, 44B, 133–149, 1992. 2990
Swietlicki, E.: European source region identification of long range transported ambient aerosol based on PIXE analysis and related techniques, Ph.D. thesis, Lund University, Sweden, 1989. 2994, 3025
Thomas, V. M., Bedford, J. A., and Cicerone, R. J.: Bromine emissions from leaded gasoline, Geophys. Res. Lett., 24, 1371–1374, 1997. 2994
Toumi, R.: BrO as a sink for dimethylsulphide in the marine atmosphere, Geophys. Res. Lett., 21, 117–120, 1994. 2998
Troy, R. C. and Margerum, D. W.: Non-metal redox kinetics: Hypobromite and hypobromous acid reactions with iodide and with sulfite and the hydrolysis of bromosulfate, Inorg. Chem., 30, 3538–3543, 1991. 2998
Tuckermann, M., Ackermann, R., Gölz, C., Lorenzen-Schmidt, H., Senne, T., Stutz, J., Trost, B., Unold, W., and Platt, U.: DOAS-observation of halogen radical-catalysed arctic boundary layer ozone destruction during the ARCTOC campaign 1995 and 1996 in Ny-Ålesund, Spitzbergen, Tellus, 49B, 533–555, 1997. 2997
Turekian, V. C.: The application of chemical and isotopic tracers to characterize aerosol sources and processing in marine air, Ph.D. thesis, University of Virginia, 2000. 2993, 3021
Turekian, V. C., Macko, S. A., and Keene, W. C.: Application of stable sulfur isotopes to differentiate sources of size-resolved particulate sulfate in polluted marine air at Bermuda during spring, Geophys. Res. Lett., 28, 1491–1494, 2001. 2975, 3021
Turekian, V. C., Macko, S. A., and Keene, W. C.: Concentrations, isotopic compositions, and sources of size-resolved, particulate organic carbon and oxalate in near-surface marine air at Bermuda during spring, J. Geophys. Res., 108D, 4157, 10.1029/2002JD002 053, 2003. 2971, 2975, 2979, 3021
Turn, S. Q., Jenkins, B. M., Chow, J. C., Pritchett, L. C., Campbell, D., Cahill, T., and Whalen,

S. A.: Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels, J. Geophys. Res., 102D, 3683–3699, 1997. 3032

Vogt, R., Crutzen, P. J., and Sander, R.: A mechanism for halogen release from sea-salt aerosol in the remote marine boundary layer, Nature, 383, 327–330, 1996. 2972, 2979, 2980, 2996, 2998

Vogt, R., Sander, R., von Glasow, R., and Crutzen, P. J.: Iodine chemistry and its role in halogen activation and ozone loss in the marine boundary layer: A model study, J. Atmos. Chem., 32, 375–395, 1999. 2972, 2998

von Glasow, R., Sander, R., Bott, A., and Crutzen, P. J.: Modeling halogen chemistry in the marine boundary layer. 1. Cloud-free MBL, J. Geophys. Res., 107D, 4341, 10.1029/2001JD000 942, 2002a. 2982

von Glasow, R., Sander, R., Bott, A., and Crutzen, P. J.: Modeling halogen chemistry in the marine boundary layer. 2. Interactions with sulfur and the cloud-covered MBL, J. Geophys. Res., 107D, 4323, 10.1029/2001JD000 943, 2002b. 2984

Wagner, T. and Platt, U.: Satellite mapping of enhanced BrO concentrations in the troposphere, Nature, 395, 486–490, 1998. 2983, 2988, 3028

Wagner, T., Leue, C., Wenig, M., Pfeilsticker, K., and Platt, U.: Spatial and temporal distribution of enhanced boundary layer BrO concentrations measured by the GOME instrument aboard ERS-2, J. Geophys. Res., 106D, 24 225–24 235, 2001. 2988, 3028

Wedepohl, K. H.: The composition of the continental crust, Geochim. Cosmochim. Acta, 59, 1217–1232, 1995. 2991, 3032

Willeke, K.: Performance of the slotted impactor, Am. Ind. Hyg. Assoc. J., 36, 683–691, 1975. 2968

Wilson, T. R. S.: Salinity and the major elements of sea water, in: Chemical Oceanography, Vol. 1, 2nd Ed., edited by Riley, J. P. and Skirrow, G., pp. 365–413, Academic Press, 1975. 3019, 3032

WMO: Scientific Assessment of Ozone Depletion: 1998, Global Ozone Research and Monitoring Project, Report no. 44, World Meteorological Organization, Geneva, 1998. 2966, 2994

Woodcock, A. H.: Salt nuclei in marine air as a function of altitude and wind force, J. Meteorol., 10, 362–371, 1953. 2987

Yokouchi, Y., Machida, T., Barrie, L. A., Toom-Sauntry, D., Nojiri, Y., Fujinuma, Y., Inuzuka, Y.,

Table 1. Concentrations of selected elements in sea water at 3.5 % salinity (Wilson, 1975) and element ratios used to calculate enrichment factors

	based on mass		based on amount of substance	
Cl	19.35	g/kg	0.5459	mol/kg*
Br	0.0673	g/kg	0.0008423	mol/kg*
Na	10.77	g/kg	0.4685	mol/kg*
Mg	1.290	g/kg	0.05306	mol/kg*
Ca	0.4121	g/kg	0.01028	mol/kg*
Br/Na	0.00625	kg/kg	0.00180	mol/mol
Br/Cl	0.00348	kg/kg	0.00154	mol/mol
Br/Mg	0.0522	kg/kg	0.0159	mol/mol
Br/Ca	0.163	kg/kg	0.0819	mol/mol
Cl/Na	1.797	kg/kg	1.165	mol/mol

*Note that this refers to kg of sea water and not to kg of solvent. It thus is not a molality.

Li, H.-J., Akimoto, H., and Aoki, S.: Latitudinal distribution of atmospheric methyl bromide: measurements and modeling, Geophys. Res. Lett., 27, 697–700, 2000. 2994

Zafiriou, O. C.: Photochemistry of halogens in the marine atmosphere, J. Geophys. Res., 79, 2730–2732, 1974. 2966

Zhou, M. Y., Yang, S. J., Parungo, F. P., and Harris, J. M.: Chemistry of marine aerosols over the western Pacific Ocean, J. Geophys. Res., 95D, 1779–1787, 1990. 3024

Table 2. Bromine depletions measured in marine aerosol samples

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
AMS9298	Amsterdam Island (38°S, 78°E) Jan 1992–Jul 1998	CI IC	Na	Fig. 3	Baboukas (2000) and Baboukas (unpublished)
ARA95	Arabian Sea cruise May–Aug 1995 (R/V Meteor)	bulk IC	Na	Fig. 2	Johansen et al. (1999)
ATL77	Atlantic cruise Jun 1977 (R/V Capricorne)	bulk NAA	Na	Fig. 2	Kritz and Rancher (1980) and Rancher and Kritz (1980)
ATL7879	Atlantic cruise Sep 1978–Apr 1979 (polyester sailboat)	CI PIXE	K	Fig. 3	Maenhaut et al. (1981b)[5] and Maenhaut et al. (1983)
ATL90	Atlantic cruise Jan–Mar 1990 (R/V Meteor)	SFU NAA	Na	Figs. 2, 5	Maenhaut et al. (unpublished)
ATL94	Atlantic cruise Oct–Nov 1994 (R/V Polarstern)	SFU PIXE	Ca	Figs. 2, 5, 7	Van Dingenen (pers. comm., 1996)
ATL96	Atlantic cruise Apr 1996 (R/V Seward Johnson)	HVDVI IC	Na	Figs. 2, 5	Johansen et al. (2000)
ATL96b	Atlantic cruise Oct–Nov 1996 (R/V Polarstern)	CI IC	Na	Figs. 2, 3, 5, 7	Baboukas et al. (2000)[5]
BAB8897	Barbados (13°N, 59°W) Aug 1988–Dec 1997 (AEROCE)	bulk NAA	Na	Figs. 2, 11	Arimoto et al. (1995)[5] and Arimoto et al. (unpublished)
BAB94	Barbados (13°N, 59°W) Apr–May 1994 (AEROCE)	CI NAA	Na	Fig. 3	Arimoto et al. (unpublished)
BEM8897	Bermuda (32°N, 64°W) Jul 1988–Dec 1997 (AEROCE)	bulk NAA	Na	Figs. 2, 11	Arimoto et al. (1995)[5] and Arimoto et al. (unpublished)
BEM93	Bermuda (32°N, 64°W) Apr–May, Aug–Sep 1993 (AEROCE)	CI NAA	Na	Fig. 3	Arimoto et al. (unpublished)

Table 2. Continued

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
BEM96	Bermuda (32°N, 64°W) Apr–May 1996 (AEROCE)	CI NAA	Na	Fig. 3	Keene and Savoie (1998)[5] and Keene and Savoie (1999)[5]
BEM97	Bermuda (32°N, 64°W) May 1997 (AEROCE)	CI + bulk IC[6]	Na	Figs. 2, 3	Keene et al. (2002)[5]
BEM98	Bermuda (32°N, 64°W) Apr–Jun 1998 (AEROCE)	CI + bulk IC[6]	Mg	Fig. 3	Turekian (2000), Turekian et al. (2001) and Turekian et al. (2003)
BIR9196	Birkenes, Norway (58°N, 8°E) Jan 1991–Mar 1996	SFU NAA	Na	Figs. 2, 5, 12	Maenhaut et al. (1996a)[5] and Maenhaut et al. (unpublished)
CGR79	Cape Grim, Australia (41°S, 145°E) Sep 1979	CI + SFU PIXE	K	Fig. 3	Andreae (1982)
CGR94	Cape Grim, Australia (41°S, 145°E) Mar–Jun 1994	CI IC	Na	see note[4]	Ayers et al. (1999)
CGR95	Cape Grim, Australia (41°S, 145°E) Nov–Dec 1995 (ACE-1)	in situ PALMS	CI	Sect. 4	Murphy et al. (1997)
CGR9698	Cape Grim, Australia (41°S, 145°E) Jan 1996–Jul 1998	bulk IC	Na	Figs. 2, 10	Ayers et al. (1999) and Ayers (pers. comm., 1999)
CRE97	Finokalia, Crete, (35°N, 26°E) Feb–Oct 1997	CI IC	Mg	Fig. 3	Mihalopoulos et al. (1997)[5] and Kouvarakis and Mihalopoulos (unpubl.)
CRE99	Nopigia, Crete (36°N, 24°E) May 1999	CI IC	Mg	Fig. 3	Kouvarakis et al. (2002)
CRO9698	Crozet (46°S, 52°E) Jul 1996–Mar 1999	bulk IC	Na	Fig. 2	Baboukas (2000) and Baboukas (unpublished)

Table 2. Continued

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
ENE79	Enewetak, Pacific (11°N, 162°E) Apr–May 1979 (dry season) and Jul–Aug 1979 (wet season) (SEAREX)	Cl + bulk NAA	Na	Fig. 3	Duce et al. (1983)
HAR83	Isle of Harris, UK (58°N, 7°W) Apr–May 1983	bulk XRF[7]	Na	Fig. 2	Sturges (1990)
HAW62	Hawaii (20°N, 155°W) May 1962	silver rods NAA	Cl	Fig. 2	Duce et al. (1963)
HAW63	Hawaii (20°N, 155°W) Summer 1963	Cl NAA	Cl	Fig. 3	Duce et al. (1965)
HAW66	Hawaii (20°N, 155°W) Summer 1966	Cl NAA	Cl	Fig. 3	Duce et al. (1967)
HAW67	Oahu, Hawaii (22°N, 158°W) Fall 1967	Cl NAA	Cl	Fig. 3	Duce and Woodcock (1971)
HAW69	Oahu, Hawaii (22°N, 158°W) Jul/Aug 1969	Cl NAA	Cl	Figs. 2, 3	Moyers and Duce (1972)
HAW99	Oahu, Hawaii (22°N, 158°W) Aug–Oct 1999	Cl + bulk IC[6]	Mg	Figs. 2, 3, 5	Pszenny et al. (manuscript in preparation)
HAW99b	Oahu, Hawaii (22°N, 158°W) Sep 1999	bulk IC	Na	Fig. 9	Phillips et al. (2000) and Huebert et al. (unpublished)
INDXX	Mahabaleshwar, India (18°N, 74°E) during summer monsoon (year=?)	Cl NAA	Na	Fig. 3	Sadasivan (1980)
IND73	Indian Ocean cruise May–Jun 1973	Cl NAA	Na	Fig. 3	Sadasivan (1978), Sadasivan (1980)

Table 2. Continued

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
IND99	Indian Ocean flights Feb–Mar 1999 (INDOEX)	SFU IC	Na	Fig. 2	Gabriel et al. (2002) and Gabriel (pers. comm., 2001)
JAB9596	Jabiru, Australia (13°S, 133°E) May 1995–Dec 1996	SFU NAA	Na	Figs. 2, 5	Maenhaut et al. (2000)[5] and Maenhaut et al. (unpublished)
MHD8994	Mace Head, Ireland (53°N, 10°W) Aug 1989–Aug 1994 (AEROCE)	bulk NAA	Na	Figs. 2, 11	Arimoto et al. (1995)[5] and Arimoto et al. (unpublished)
MHD93	Mace Head, Ireland (53°N, 10°W) Jun–Aug 1993 (AEROCE)	Cl NAA	Na	Fig. 3	Arimoto et al. (unpublished)
MOR81	Morecambe Bay, UK (54°N, 3°W) Oct–Dec 1981	bulk XRF[7]	Na	see note[4]	Sturges and Harrison (1986a)
MOR8283	Morecambe Bay, UK (54°N, 3°W) Dec 1982–Jan 1983 and Sep–Oct 1983	bulk XRF[7]	Na	see note[4]	Sturges and Harrison (1986b)
MQI9597	Macquarie Island (55°S, 159°E) Dec 1995–Apr 1997	SFU IC	Na	Fig. 2	Ayers et al. (1999)
NOS91	North Sea cruise Sep 1991 (NOSE)	SFU NAA	Na	Figs. 2, 5	François et al. (1993)[5] and Maenhaut et al. (unpublished)
NOS92	North Sea research platform (55°N, 7°E) Sep 1992 (ASE)	SFU NAA	Na	Figs. 2, 5, 6	François and Maenhaut (1994)[5] and Maenhaut et al. (unpublished)
NZ83	New Zealand (35°S, 173°E) Jun–Aug 1983 (SEAREX)	Cl + bulk NAA	Na	Figs. 3, 5	Arimoto et al. (1990) and Pszenny (1987)[5]

Table 2. Continued

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
PAC79	Pacific cruise Apr–Jun 1979 (polyester sailboat)	CI PIXE	K	Fig. 3	Maenhaut et al. (1983)
PAC82	Pacific cruise Jun–Aug 1982 (R/V Conrad)	CI + bulk PIXE	Na, K	Figs. 2, 3	Raemdonck et al. (1986)
PAC8586	Pacific cruise Dec 1985–Feb 1986 (R/V Xiangyanghong)	CI + bulk NAA	Na	Fig. 3	Zhou et al. (1990)
PD86	Drake Passage cruise Mar–Apr 1986 (R/V Polar Duke)	CI IC[6]	Na	Figs. 3, 5	Pszenny et al. (1989)[5]
PSI91	North East Pacific cruise May 1991 (PSI-3)	CI IC	Na	Fig. 3	Howell et al. (1998)[5]
PUR71	Puerto Rico (18°N, 66°W) Nov 1971	CI NAA	Na	Fig. 3	Martens (1973)
RITS90	Equatorial Pacific cruise Jan–Feb 1990 (RITS)	CI IC[6]	Mg	Fig. 3	Pszenny (1992)[5]
RITS91	Atlantic cruise Jul–Sep 1991 (RITS)	CI IC	Na	Figs. 3, 5	Pszenny et al. (1993)[5]
SAM76	Samoa (14°S, 171°W) Jul–Sep 1976	CI PIXE	Cl	Fig. 3	Maenhaut et al. (1981a)
SAM81	Samoa (14°S, 171°W) Jan–Feb 1981 (wet season) and Jul–Aug 1981 (dry season) (SEAREX)	CI + bulk NAA + IC[6]	Na	Fig. 3	Arimoto et al. (1987) and Pszenny (1987)[5]

Table 2. Continued

Data set	Location Date (Campaign[1])	Sampling[2] Analysis[3]	*EF* vs.	Result[4]	Reference
SWE8586	Utlängan (56°N, 16°E), Landsort (59°N, 18°E), and Svenska Högarna (59.5°N, 19.5°E), Sweden Mar 1985–Dec 1986	SAM PIXE	Na	see note[4]	Swietlicki (1989)
TEN8997	Izaña, Tenerife (29°N, 17°W) May 1989–Dec 1997 (AEROCE)	bulk NAA	Na	Sect. 4.2	Arimoto et al. (1995)[5] and Arimoto et al. (unpublished)
TEN94	Punta del Hidalgo, Tenerife (29°N, 17°W) Jul 1994 (AEROCE)	CI NAA	Na	Fig. 3	Arimoto et al. (unpublished)
TEX91	Texel, The Netherlands (53°N, 5°E) Sep 1991 (NOSE)	SFU NAA	Na	Figs. 2, 5	François and Maenhaut (1994)[5], François et al. (1993)[5] and Maenhaut et al. (unpublished)

All data sets listed as unpublished are based on measurement methods presented in Sect. 2.1.

[1] The acronyms of the field campaigns are: ACE-1 = First Aerosol Characterization Experiment; AEROCE = Atmosphere/Ocean Chemistry Experiment; ASE = EUROTRAC subproject Air-Sea Exchange; EUROTRAC = European Experiment on Transport and Transformation of Environmentally Relevant Trace Constituents in the Troposphere over Europe; INDOEX = Indian Ocean Experiment; NOSE = North Sea Experiment; PSI-3 = Third Pacific Sulfur/Stratus Investigation; RITS = Radiatively Important Trace Species; SEAREX = Sea/Air Exchange; SOAPEX = Southern Ocean Atmospheric Photochemistry EXperiment. For ship cruises, the name of the ship is given.

[2] The sampling devices are: bulk = aerosol sampled in bulk on filters; CI = cascade impactor; HVDVI = high-volume dichotomous virtual impactor; SAM = stationary aerosol monitor as described by Hansson and Nyman (1985); SFU = 2-stage stacked filter unit.

[3] The analytical methods are: IC = ion chromatography; NAA = neutron activation analysis; PIXE = particle (or 'proton') induced X-ray emission; PALMS = particle analysis by laser mass spectrometry; XRF = X-ray fluorescence.

Table 2. Continued

[4] CGR94: Table 4 in Ayers et al. (1999) lists a mean value of $EF = 0.51$; MOR81: A good correlation between Br and Pb was found with only a small sea-salt contribution; MOR8283: $EF \approx 0$ after correction for Br from vehicles; SWE8586: $EF > 1$ for submicrometer particles.
[5] This reference contains general information about the field campaign. However, it does not contain the aerosol bromine data that we present here.
[6] The reference element was analyzed using atomic absorption spectroscopy (AAS).
[7] The reference element was analyzed using flame photometry.

Table 3. Measurements of gas-phase bromine species (other than BrO)

Data set	Location Date (Campaign)	Sampling Analysis[1]	Result	Reference
ATL77-G	Atlantic (0°N, 0°W) Jun 1977	filter + LiOH NAA	3.4 pmol/mol	Kritz and Rancher (1980)
ATL80-G	North and South Atlantic (20°N to 30°S) Oct–Nov 1980	?[2] ?[2]	2.6±1.1 pmol/mol during day 3.2±1.4 pmol/mol at night	Berg et al. (1982)
BEM74-G	Bermuda (32°N, 64°W) Jun–Oct 1974	filter + LiOH NAA	6.7 pmol/mol	Rahn et al. (1976)
HAR83-G	Isle of Harris, UK (58°N, 7°W) Apr–May 1983	filter + KOH XRF	7.9 pmol/mol	Sturges (1990)
HAW63-G	Hawaii (20°N, 155°W) summer 1963	K_2CO_3 impinger NAA	2 to 12 pmol/mol	Duce et al. (1965)
HAW69-G	Hawaii (20°N, 155°W) Jul/Aug 1969	activated charcoal NAA	13 to 20 pmol/mol (probably includes organic bromine as well)	Moyers and Duce (1972)
HAW99-G	Hawaii (20°N, 155°W) Sep 1999	filter + K_2CO_3 IC	4.9 pmol/mol daytime average 2.8 pmol/mol nighttime average (Fig. 8)	Perner et al. (2000) and Pszenny et al. (manuscript in preparation)
MOR8283-G	Morecambe Bay, UK (54°N, 3°W) XRF Dec 1982–Jan 1983 and Sep–Oct 1983	filter + KOH	2.8±1.7 pmol/mol	Sturges and Harrison (1986b)
NY96-G	Long Island, New York, USA (41°N, 72°W) Jun 1996	APCIMS	small Br_2 signal detected (but did not exceed detection limit of 6 pmol/mol)	Spicer et al. (1998) and Foster et al. (2001)

[1] APCIMS = atmospheric-pressure chemical ionization mass spectrometry; IC = ion chromatography; NAA = neutron activation analysis; XRF = X-ray fluorescence.
[2] The sampling and analysis methods were not specified by Berg et al. (1982).

Table 4. DOAS Measurements of BrO in the mbl and over inland saline water bodies

Data set	Location Date (Campaign[1])	Result Analysis	Reference
ATL00-G	Atlantic (54°N to 34°S) Oct 2000 (Polarstern)	two days (around 35°N) with BrO average of 0.7 pmol/mol and a maximum of 2.4 pmol/mol, below DL elsewhere	Leser et al. (2003)
CRT00-G	Finokalia, Crete (35°N, 26°E) Jul–Aug 2000	BrO below detection limit of 0.7 to 1.5pmol/mol	Hönninger (2002)
GOME95-G	global Jul–Dec 1995 (GOME)	first evidence for tropospheric BrO in the GOME data set	Hegels et al. (1998)
GOME96-G	southern hemisphere (40 to 77°S) Sep 1996 (GOME)	tropospheric BrO detected (mainly in the Antarctic)	Wagner and Platt (1998)
GOME97a-G	northern hemisphere (40 to 90°N) Feb–Jul 1997 (GOME)	tropospheric BrO detected (mainly in the Arctic)	Richter et al. (1998)
GOME97b-G	global Apr–Oct 1997 (GOME)	tropospheric BrO detected (mainly in the Arctic)	Chance (1998)
GOME97c-G	global 1997 (GOME)	tropospheric BrO detected over Caspian Sea and over ocean bays where sea ice exists	Wagner et al. (2001)
GSL00-G	Great Salt Lake, USA (41°N, 112°E) Oct 2000	up to 6 pmol/mol BrO	Stutz et al. (2002)
HAW99b-G	Hawaii (20°N, 155°W) Sep 1999	BrO below detection limit of 2 pmol/mol	Pszenny et al. (manuscript in preparation)

Table 4. continued

Data set	Location Date (Campaign[1])	Result Analysis	Reference
ISR97-G	Dead Sea, Israel (31°N, 36°E) May–Jun 1997	up to 176 pmol/mol BrO	Hebestreit et al. (1999) and Matveev et al. (2001)
MHD96-G	Mace Head, Ireland (53°N, 10°W) Jul-Aug 1996 (EASE96)	BrO close to detection limit (estimate of 0.3 to 1.8 pmol/mol)	Allan (1998) and James et al. (2000)
MHD97a-G	Mace Head, Ireland (53°N, 10°W) Apr–May 1997 (EASE97)	BrO close to detection limit (estimate of 1.1 to 2.5pmol/mol)	Allan (1998) and James et al. (2000)
MHD97b-G	Mace Head, Ireland (53°N, 10°W) Apr–Jun 1997 (EASE97)	BrO below detection limit of 1.69 pmol/mol	Alicke (1997)
MHD98-G	Mace Head, Ireland (53°N, 10°W) Sep–Oct 1998 (PARFORCE)	BrO below detection limit of about 1 pmol/mol	Hönninger (1999)
SAOZ9798-G	global 1997 and 1998 (GOME, SAOZ)	comparing GOME with SAOZ implies 1 to 2 pmol/mol tropospheric BrO if it is distributed homogeneously	Pundt et al. (2000)
TEN97-G	Tenerife (29°N, 17°W) Jun-Jul 1997 (ACE 2)	average of 3 pmol/mol BrO but detection uncertain due to high scatter	Allan (1998)
WEY96a-G	Weybourne, UK (53°N, 1°E) Oct 1996	BrO below detection limit of 2 pmol/mol	Allan (1998)
WEY96b-G	Weybourne, UK (53°N, 1°E) Oct 1996	BrO below detection limit of 2.59 pmol/mol	Alicke (1997)

[1] ACE 2 = Aerosol Characterisation Experiment 2; EASE = East Atlantic Summer Experiment; GOME = Global Ozone Monitoring Experiment; PARFORCE = Particle Formation and Fate in the Coastal Environment; Polarstern = Polarstern cruise leg ANT XVIII/1; SAOZ = Systeme d'Analyse par Observation Zenitale.

Table 5. Bromine measured in marine rain samples

Data set	Location Date (Campaign[1])	Analysis[2]	*EF* vs.	Result	Reference
AMS9099-R	Amsterdam Island (38°S, 78°E) Jan 1991–Mar 1999	IC	Na	mean EF = 0.939	Baboukas (2000) and Baboukas (unpublished)
CGR9697-R	Cape Grim, Australia (41°S, 145°E) Jun 1996–Jan 1997	IC	Na	EF=0.613±0.022 (similar to aerosol EF)	Ayers et al. (1999)
CRO9199-R	Crozet (46°S, 52°E) Nov 1991–Mar 1999	IC	Na	mean EF = 0.963	Baboukas (2000) and Baboukas (unpublished)
HAW62-R	Hawaii (20°N, 155°W) May 1962	NAA	Cl	EF = 2	Duce et al. (1963)
HAW63-R	Hawaii (20°N, 155°W) summer 1963	NAA	Cl	EF = 0.7 to 5	Duce et al. (1965), Seto et al. (1969)
NZ83-R	New Zealand (35°S, 173°E) Jun–Aug 1983 (SEAREX)	IC	Na[3]	mean EF = 1.08	Pszenny (1987)[4]
IND7175-R	Mahabaleshwar and vicinity, India (18°N, 74°E) 1971–1975	NAA	Na	EF = 0.9 to 3.6	Sadasivan and Anand (1979)

Table 5. Continued

Data set	Location Date (Campaign[1])	Analysis[2]	EF vs.	Result	Reference
IND99-R	Indian Ocean cruise Feb–Mar 1999 (INDOEX)	IC	Na	$EF \approx 1$	Granat et al. (2002)
INDXX-R	Mahabaleshwar, India (18°N, 74°E) during summer monsoon (year=?)	NAA	Na	EF = 3.6±1.6	Sadasivan (1980)
KER9398-R	Kerguelen (49°S, 70°E) Jan 1993–Nov 1998	IC	Na	mean EF = 0.958	Baboukas (2000) and Baboukas (unpublished)
PUR71-R	Puerto Rico (18°N, 66°W) Nov 1971	NAA	Na	EF 30 % higher than for aerosol	Martens and Harriss (1973)
SAM81-R	Samoa (14°S, 171°W) Jan–Feb 1981 (wet season) and Jul–Aug 1981 (dry season) (SEAREX)	IC	Na	mean EF = 0.99 (wet seasaon) mean EF = 1.34 (dry season)	Pszenny et al. (1982)[4]
TAS83-R	Tasman Sea cruise Sep 1983 (SEAREX)	IC	Na[3]	mean EF = 0.82	Pszenny (1987)[4]

[1] Campaign names are described in footnote of Table 2.
[2] Analytical methods are described in footnote of Table 2.
[3] The reference element was analyzed using atomic emission spectrophotometry (AES).
[4] This reference contains general information about the field campaign. However, it does not contain the rainwater bromine data that we present here.

Table 6. Elemental Br/Na mass ratios in different materials

Material	m(Br)/m(Na)	Reference
continental crust	0.0000623	Wedepohl (1995)
	0.000088	Mason and Moore (1982)
sea water	0.00625	Wilson (1975)
biomass-burning		
- aerosol (South Africa)	0.015 to 0.059	Maenhaut et al. (1996b)
- savanna fires (South Africa)	0.0176	Andreae et al. (1998)
- herbaceous and wood fuels (wind tunnel)	0.022 to 1.29	Turn et al. (1997)
biofuels		
- wood, foliage, bark, soil, ...	see note[1]	McKenzie et al. (1996)
- wood	0.007 to 0.01	Slocum et al. (1978)
- charcoal	0.014 to 0.025	Slocum et al. (1978)
- rice straw	0.028 to 0.45	Saito et al. (1994)
leaded petrol	(very large)	

[1] McKenzie et al. (1996) measured Cl but not Na. They report m(Br)/m(Cl) between <0.0013 and >8.2.

ACPD
3, 2963–3050, 2003

Table 7. Acronyms used in the text

AA	atomic absorption
AAS	atomic absorption spectroscopy
AD	aerodynamic diameter
AES	atomic emission spectrophotometry
AMS	aerosol mass spectrometry
APCIMS	atmospheric-pressure chemical ionization mass spectrometry
ATOFMS	aerosol time-of-flight mass spectrometry
CI	cascade impactor
DL	detection limit
DOAS	differential optical absorption spectroscopy
EF	enrichment factor
GMD	geometric mean diameter
IC	ion chromatography
LP-DOAS	long path DOAS
MAX-DOAS	Multi-Axis DOAS
MBL	marine boundary layer
NAA	neutron activation analysis
PALMS	particle analysis by laser mass spectrometry
PIXE	particle-induced X-ray emission
SFU	stacked filter unit
XRF	X-ray fluorescence

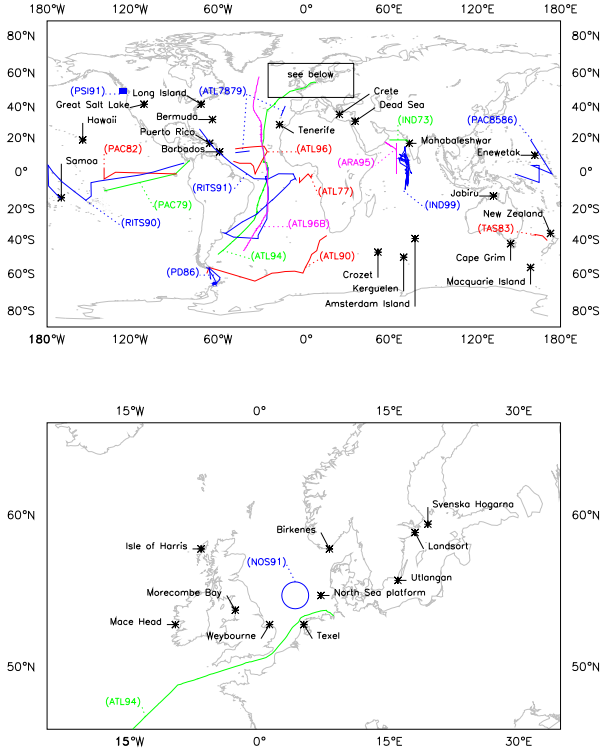

Fig. 1. Sites where atmospheric inorganic bromine has been measured in the mbl. Stationary sites are marked with asterisks. Cruise and flight tracks (colored) are labeled in parentheses using the data set names from Table 2. Some are approximate and show only the part where samples were taken. More details may be found in the original publications.

ACPD
3, 2963–3050, 2003

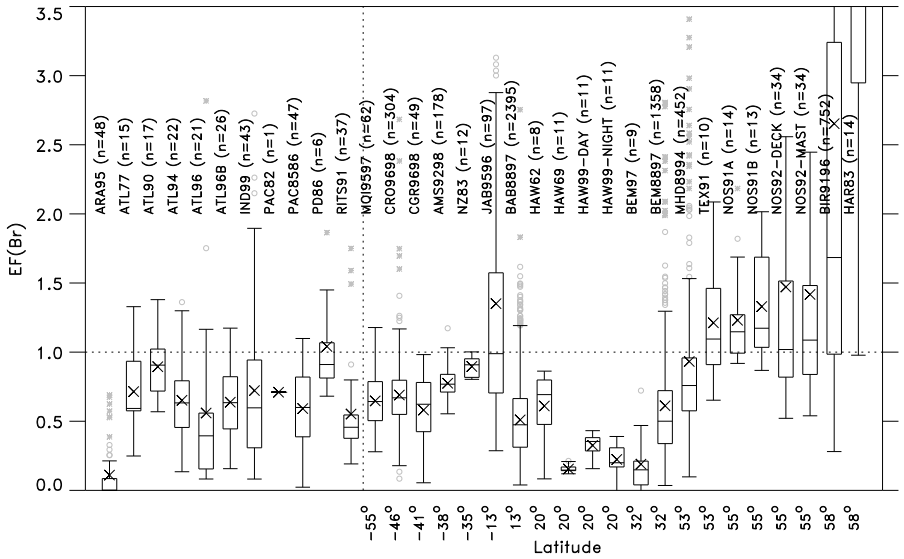

Fig. 2. Box-and-whisker plots of EF(Br) for bulk aerosol samples. For size-segregated measurements, the sum of all sizes was used. IND99 is an exception, here only the coarse mode is available. Cruises are shown in the left part. Stationary locations (right part) are sorted by latitude. The data set names are defined in Table 2. The number of samples n is given in parentheses. The plots were made following the recommodations by Frigge et al. (1989) (using their definition 6 for the quartiles): 25 % of the data are below the box and 25 % are above. Thus the box presents the middle 50 % (interquartile range). The horizontal line within the box is the median. A cross denotes the mean value. A 'step' is defined as 1.5 times the height of the box. The whiskers extend to the minimum and the maximum of the data set if these are within one step of the box. The maximum length of the whiskers is one step. Outliers more than one step away from the box are marked individually: A circle is used for those less than 2 steps away and an asterisk otherwise.

ACPD
3, 2963–3050, 2003

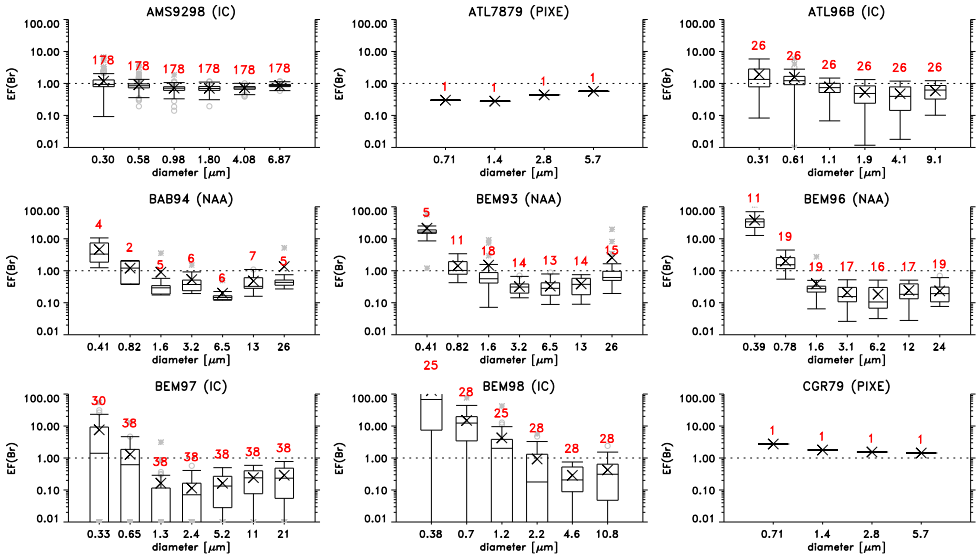

Fig. 3. Size-resolved measurements of EF(Br). The box-and-whisker plots are defined as explained in Fig. 2. The number of samples is shown in red above each box. The x-axes differ between plots. The characteristic aerosol diameter at ambient relative humidity for each impactor stage was estimated as the geometric mean diameter (GMD) of the 50 % cutoff diameters for that stage and for the preceding stage. For the top stage corresponding to the largest size fraction, we assume a GMD $\sqrt{2}$ times larger than the cutoff diameter of that stage. For the backup filter corresponding to the smallest size fraction, we assume a GMD $\sqrt{2}$ times smaller than the cutoff diameter of the preceding impactor stage. For INDXX, the sizes of the stages are not known.

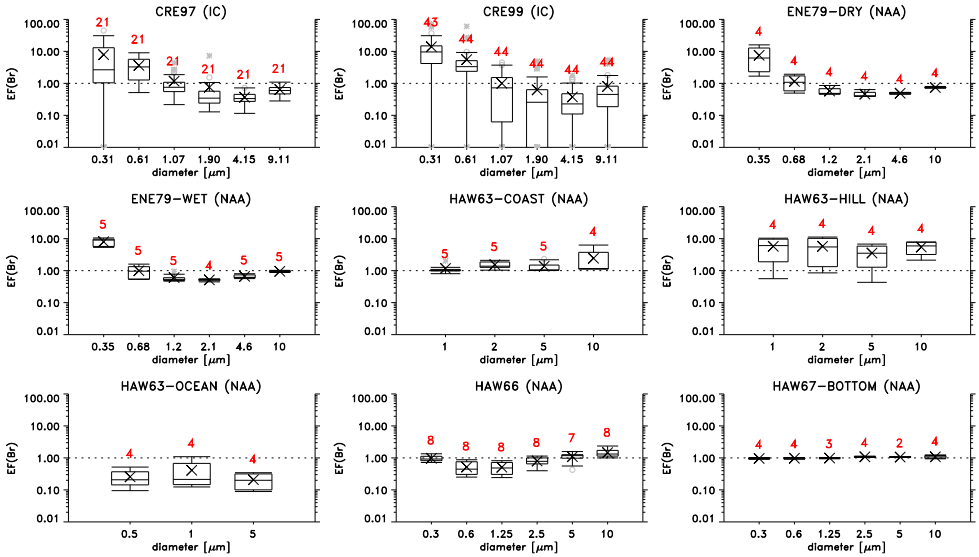

Fig. 3. (continued)

ACPD
3, 2963–3050, 2003

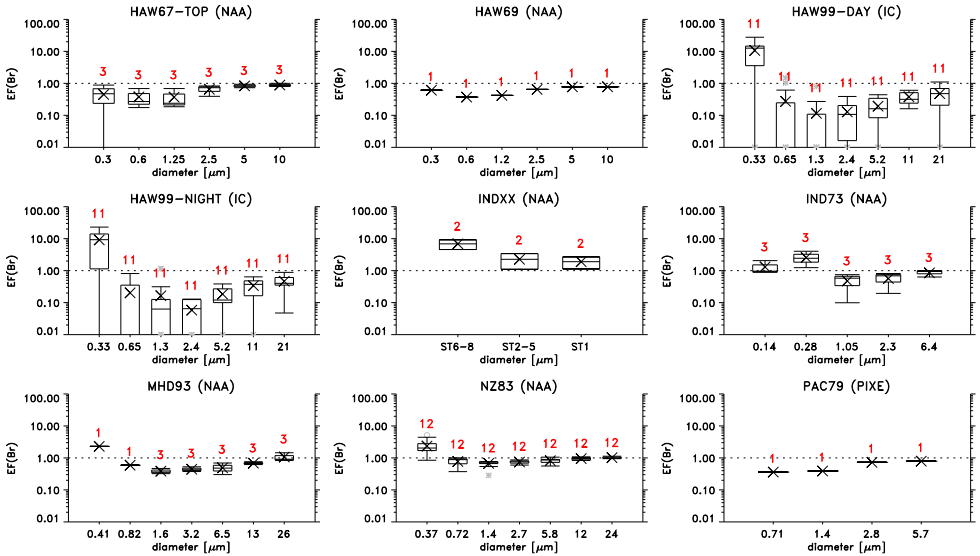

Fig. 3. (continued)

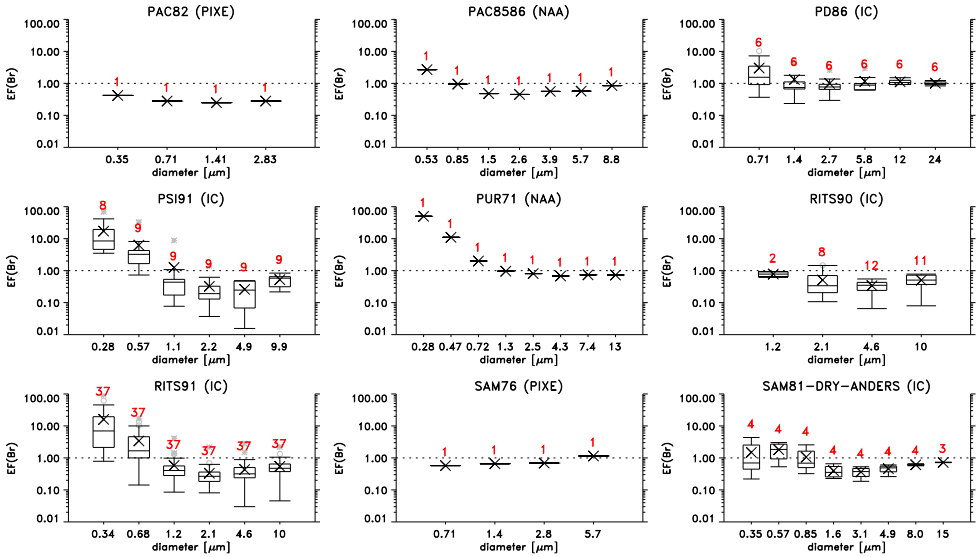

Fig. 3. (continued)

ACPD
3, 2963–3050, 2003

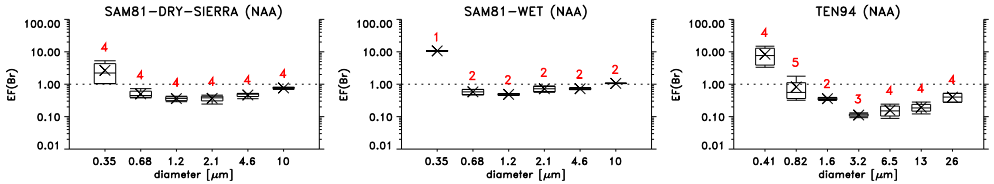

Fig. 3. (continued)

ACPD
3, 2963–3050, 2003

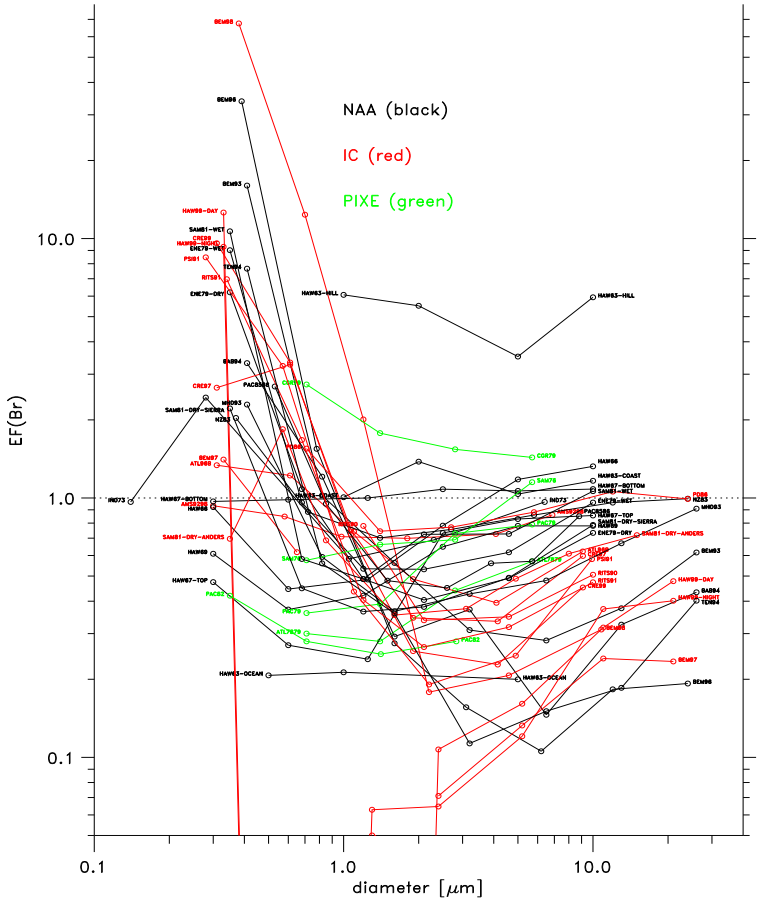

Fig. 4. Composite plot of the medians in Fig. 3. Different analytical methods are shown in different colors.

ACPD
3, 2963–3050, 2003

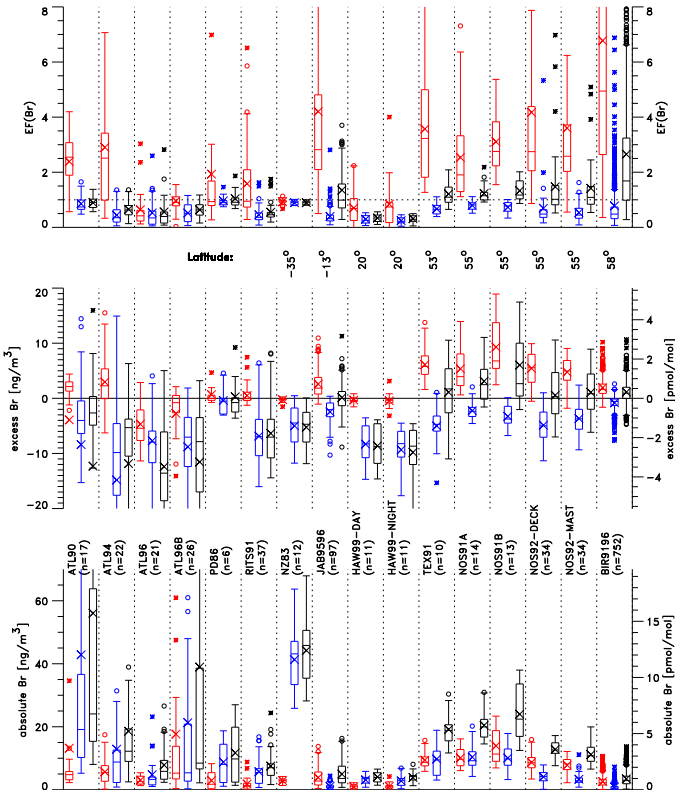

Fig. 5. *EF* (top), excess Br calculated using Eq. (3) (middle), and absolute bromine concentrations (bottom). The data set names are defined in Table 2. The number of samples *n* is given in parentheses. The plots show the SFU data sets as well as those CI data sets that include all stages for all samples. The box-and-whisker plots (as defined in Fig. 2) are shown for submicrometer (red), supermicrometer (blue) and total aerosol (black). The mixing ratio plotted at the right axis was calculated at $T = 273.15$ K and $p = 101325$ Pa.

ACPD
3, 2963–3050, 2003

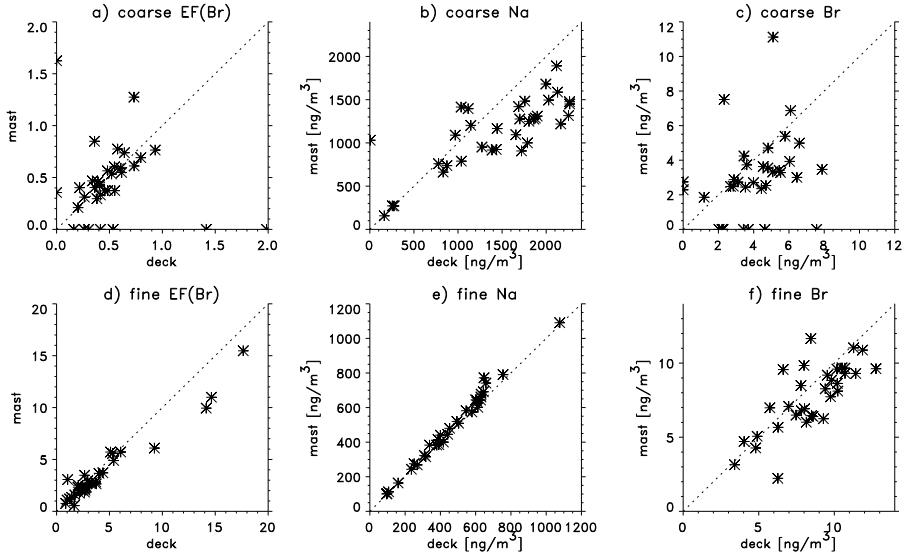

Fig. 6. Correlation between aerosol samples collected on deck (NOS92-DECK) and from the mast (NOS92-MAST) of a platform (values below the detection limit are set to zero). Data points with equal values at both heights lie on the dotted diagonal.

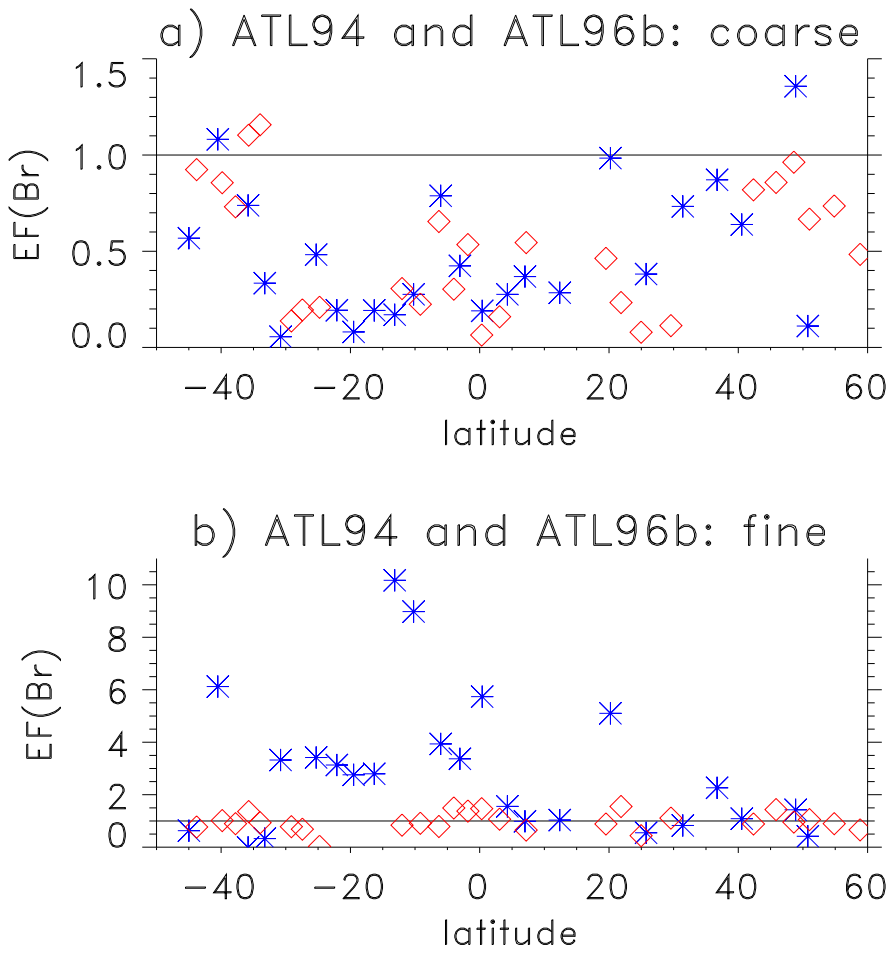

Fig. 7. Bromine enrichment factors as a function of latitude for ATL94 (blue asterisks) and ATL96b (red diamonds).

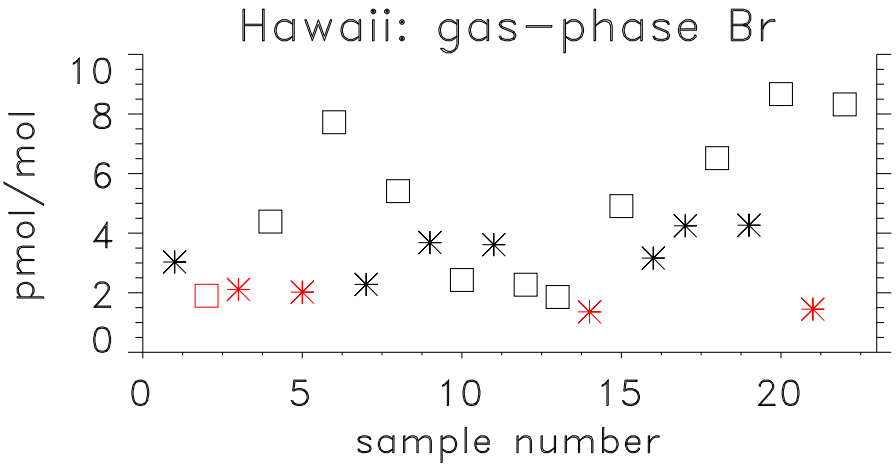

Fig. 8. Night (asterisks) and day (squares) mixing ratios of reactive gas-phase bromine compounds measured during September 1999 at Hawaii (HAW99-G). Values below DL are shown in red.

ACPD
3, 2963–3050, 2003

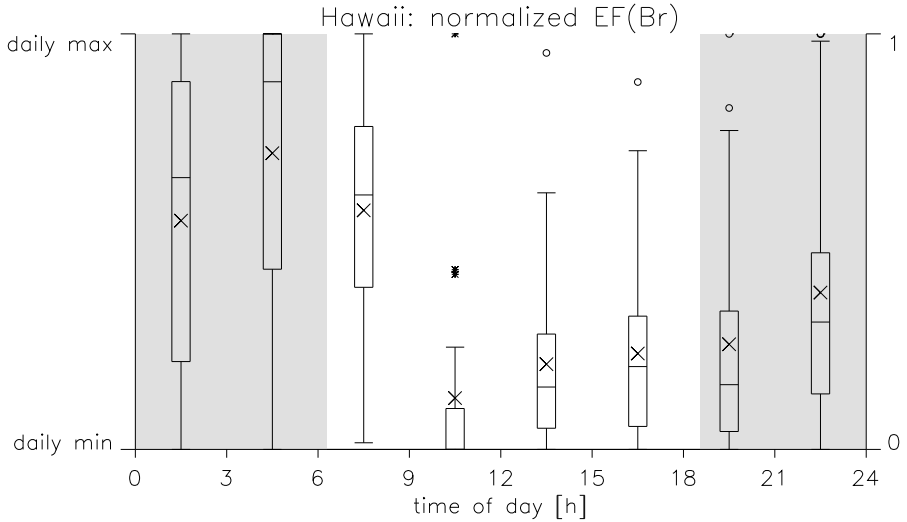

Fig. 9. Diurnal cycle of normalized EF(Br) at Hawaii (HAW99b). To eliminate the influence of day-to-day variability, the data for each day were normalized individually, where 0 represents the daily minimum and 1 the daily maximum. The box-and-whisker-plot conventions are explained in Fig. 2. The time from sunset to sunrise is shaded in grey.

ACPD
3, 2963–3050, 2003

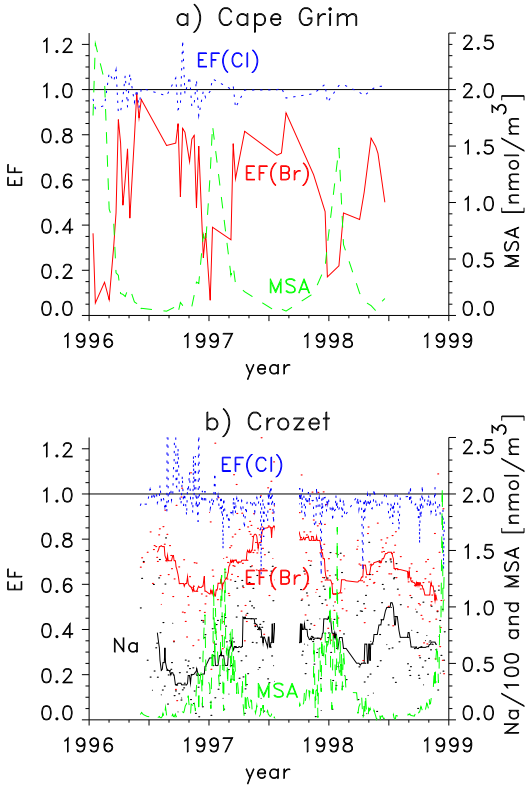

Fig. 10. Bulk EF(Br) (red, solid), EF(Cl) (blue, dotted), and MSA concentrations (green, dashed) at **(a)** Cape Grim (CGR9698) and **(b)** Crozet (CRO9698). For CRO9698, Na is also shown (black, solid). Since there is a lot of scatter in the EF(Br) and Na data for Crozet, the individual data points are shown as dots and the solid line represents the 20-point running median.

ACPD
3, 2963–3050, 2003

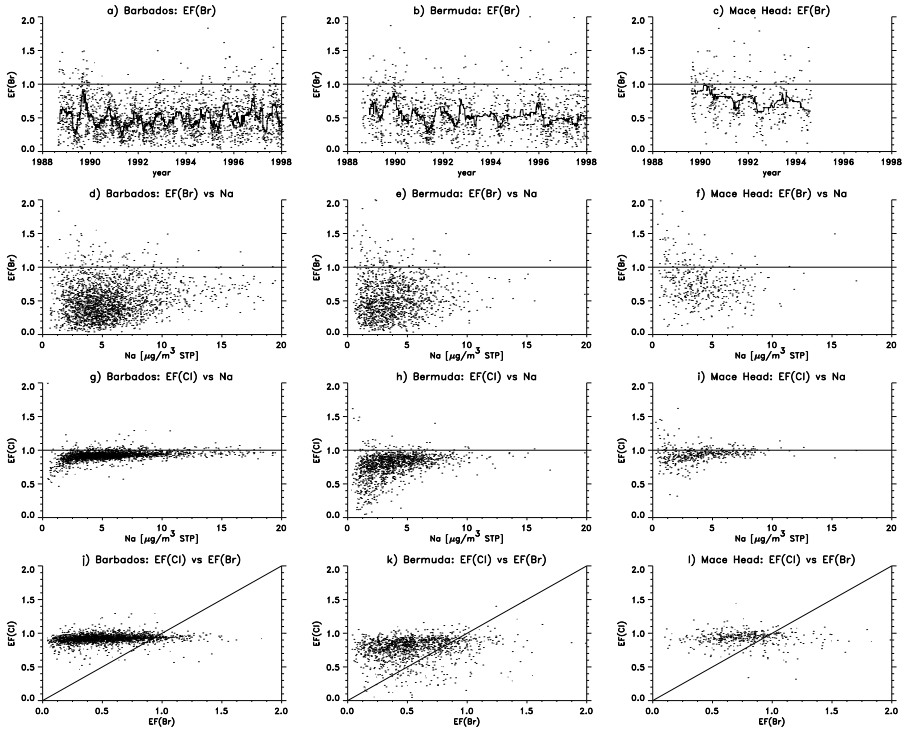

Fig. 11. Bulk AEROCE data for Barbados (BAB8897), Bermuda (BEM8897), and Mace Head (MHD8994).
(a–c) Bromine enrichment vs. time. The thick solid line is a 40-point running median. Labels for the years mark 1 January.
(d–i) Enrichment factors plotted against Na concentrations (STP refers to $T = 273.15$ K and $p = 101325$ Pa).
(j–l) A comparison between $EF(\mathrm{Cl})$ and $EF(\mathrm{Br})$. The diagonal lines divide the regions where $EF(\mathrm{Br}) < EF(\mathrm{Cl})$ (upper left) and $EF(\mathrm{Br}) > EF(\mathrm{Cl})$ (lower right).

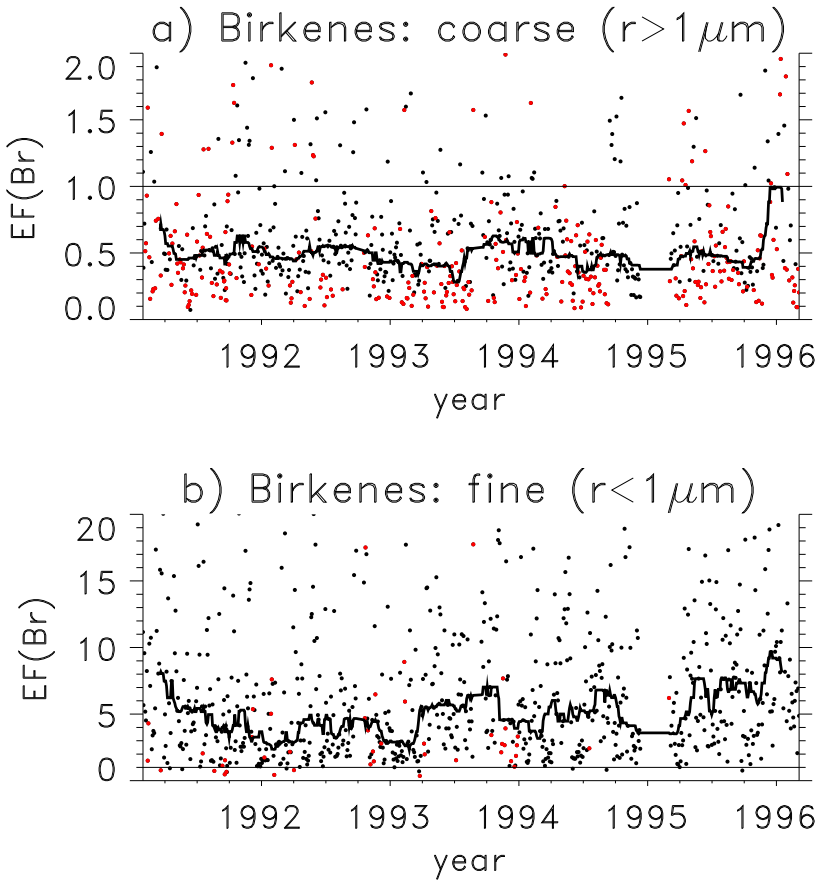

Fig. 12. Bromine enrichment measured at Birkenes (BIR9196) vs. time. The thick solid line is a 40-point running median. Labels for the years mark 1 January. In cases where measured bromine was below DL (shown in red), values were set to 50% of the DL.

ACPD
3, 2963–3050, 2003

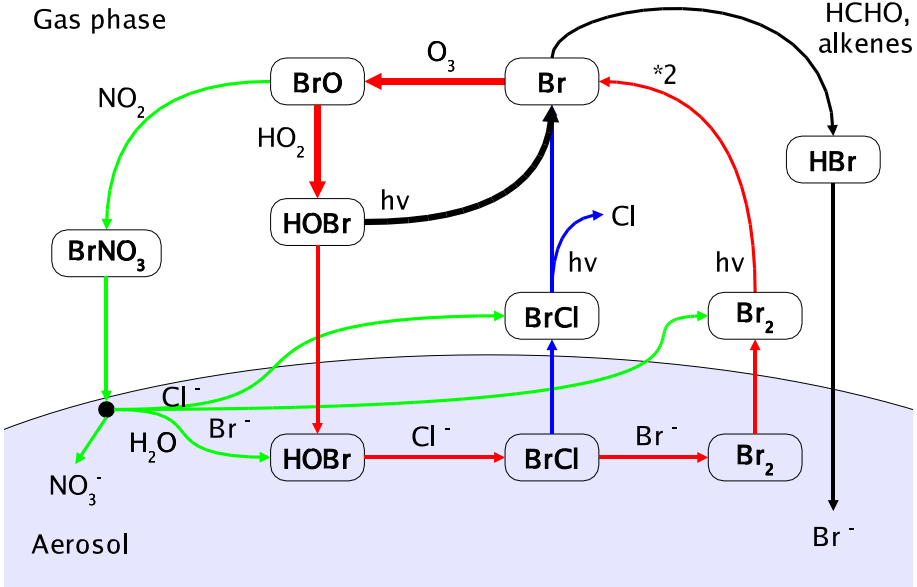

Fig. 13. Simplified reaction scheme of marine bromine chemistry.

ACPD
3, 2963–3050, 2003